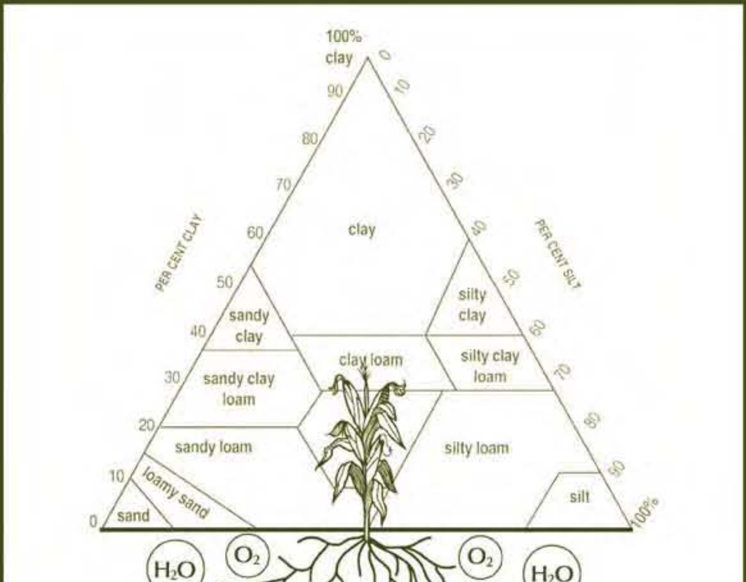
AGRONOMIC HANDBOOK

Management of Crops, Soils, and Their Fertility



J. Benton Jones, Jr.

CRC PRESS

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Preface

Agronomy is defined as that "branch of agriculture that deals with the theory and practice of field crop production and soil management." This agronomic handbook contains information on the cultures of some of the world's major agronomic grain, oil, fiber, and sugar crops and provides data on the characteristics and management of these crops and the soils on which they are grown.

The handbook is divided into multiple parts, each dealing with a specific aspect of agronomy: the major field crops; soils, their classification and characteristics; pH, liming and liming materials; fertilizers; mineral nutrition; diagnostic procedures for assessing the fertility status of soils and the nutrient element status of plants; and units and measures. This handbook is unique in that it covers both crop and soil topics and focuses on their significant aspects. Although some of the information presented is dated and will change with time, most of it will not. The appendices include a list of definitions, a glossary of botanical terms, data on nutrient requirements for major agronomic crops, a list of troublesome weeds, a key to nutrient deficiency symptoms of legumes, and a summary of the characteristics of the major elements and micronutrients.

The information in this book came from government publications, university bulletins and circulars, textbooks, journal articles, industry publications, and the Internet. The objectives are to focus on accepted basic principles and procedures and present only those aspects of each subject that will enhance knowledge of crops and soils. For example, fertilizer recommendations are not included since they are based on a range of inputs such as soil status, cropping procedures, and climatic, economic, and cultural conditions that will change with time and circumstances. Similarly, specific cultural crop practices are not included because most of them are based on local and regional climatic, economic, cultural, and other factors that will also change with time and circumstances. However, this book contains the basic information needed to develop cultural, liming, and fertilizer recommendations.

Most agronomic reference books focus on a single crop or several related crops or on a specific soil topic. They do not cover a full range of both crop and soil topics as this book does. The major objective is to cover both crops and soils, so that the reader will need only one book to locate important and useful information on both aspects of agronomy. This handbook contains a wide range of fundamental information on crops and soils. It should serve as a valuable resource for all those engaged in agronomic production, study, and research, whether as farmers, agricultural consultants or advisors, researchers, or students.

Author

J. Benton Jones, Jr., Ph.D., is professor emeritus at the University of Georgia (UGA). He retired in 1989 after completing 21 years of service. He spent 10 years as a professor of agronomy at the Ohio Agricultural Research and Development Center where he established the Ohio Plant Analysis Laboratory, the first of its kind to provide analytical and interpretive services dealing with agronomic crops. Dr. Jones joined UGA in 1968 and supervised construction of the Georgia Soil Testing and Plant Analysis Laboratory. He served as its first director until he became chairman of the Department of Horticulture in 1974. He also assisted in establishing the analytical laboratory of UGA's Institute of Ecology.

Dr. Jones has written extensively about analytical methods and developed many procedures for assaying soil and plant tissue and interpreting soil and plant analyses to aid in crop production decision making.

He was first president and later served as secretary-treasurer of the Soil and Plant Analysis Council. He has written more than 200 scientific articles, 15 book chapters, and 5 books. He established two international journals, *Communications in Soil Science and Plant Analysis* and the *Journal of Plant Nutrition,* and served as their editor for many years.

Dr. Jones earned a B.S. in agricultural science from the University of Illinois and an M.S. and Ph.D. in agronomy from Pennsylvania State University. He has traveled widely in connection with consultancies in the former Soviet Union, China, Taiwan, South Korea, Saudi Arabia, Egypt, Costa Rica, Cape Verde, India, Hungary, Kuwait, and Indonesia.

He has received many awards and recognitions for his work in soil testing and plant analysis. He is a Fellow of the American Association for the Advancement of Science, the American Society of Agronomy, and the Soil Science Society of America. The Soil and Plant Analysis Council established the J. Benton Jones, Jr. Award in his honor in 1989. The University of Horticulture in Budapest conferred an Honorary Doctorate on Dr. Jones. He is a member of Sigma Xi, Gamma Sigma Delta, and Phi Kappi Phi, and is listed in *Who's Who in America* and in several similar biographical listings.

Dr. Jones resides in Anderson, SC. He continues to write and advise growers and is experimenting with hydroponic growing systems for use in the field and greenhouse.

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Part I

Agronomic Crops

1 Production of Major Grain, Food, Oil, Fiber, and Sugar Crops

1.1 INTRODUCTION

Gary Gardner, in "Trends: From Surplus to Scarcity," a section of Worldwatch Paper 131[1] (1996) stated, "Human efforts to produce ever-greater amounts of food reached a historic pinnacle in 1981. After thousands of years of expansion, the amount of grainland under cultivation worldwide peaked, topping 732 million hectares." From the perspective of land use, the period after 1981 marks a new agricultural era, in which increasing demand for grain is met on a generally contracting base of land.

Trends in grain production — wheat, corn, and rice being the major grains — are the results of complex interactions among the influencing factors of land and fertilizer use and climatic and economic conditions.[2] This section contains tables and figures relating to world and U.S. production of the major food and feed grain, oil, fiber, and sugar crops.

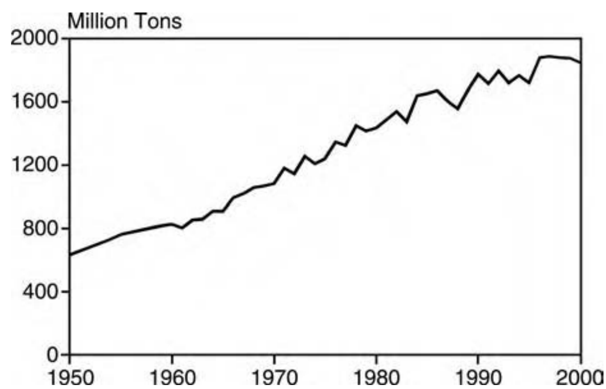


FIGURE 1.1 World grain production, 1950–2000. (*Source*: *Vital Signs 2001*, Worldwatch Institute, W.W. Norton, New York.)

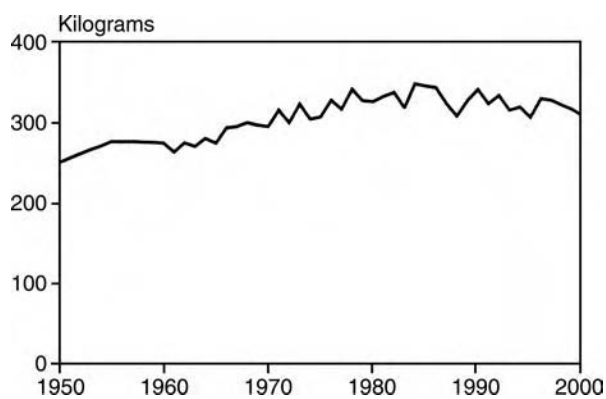


FIGURE 1.2 World grain production per person, 1950–2000. (*Source*: *Vital Signs 2001*, Worldwatch Institute, W.W. Norton, New York.)

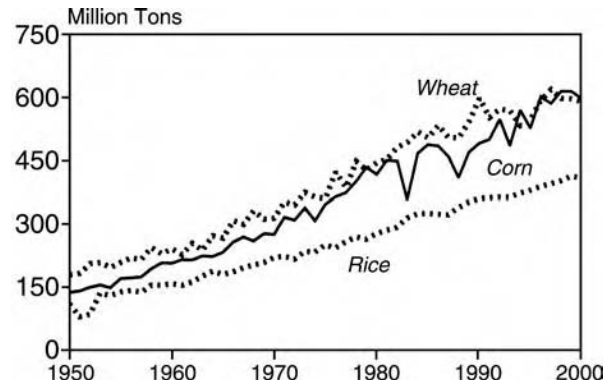


FIGURE 1.3 Wheat, corn, and rice production, 1950–2000. (*Source*: *Vital Signs 2001*, Worldwatch Institute, W.W. Norton, New York.)

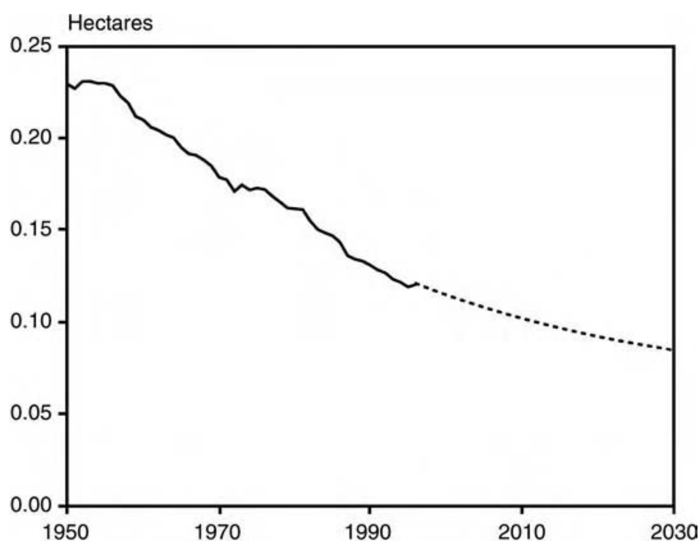


FIGURE 1.4 Harvested grain area per person, 1950–1996, with projections to 2030. (*Source*: *The Agricultural Link*, Worldwatch Institute, Washington, D.C.)

1.2 GRAIN YIELD POTENTIALS

TABLE 1.1
Maximum Attainable Crop Yield Ranges for High and Intermediate Level Inputs in Tropical, Subtropical, and Temperate Environments under Irrigated Conditions[a]

	High Input Yields (tons per hectare)			Intermediate Input Yields (tons per hectare)		
Crop Type	Tropics	Subtropics	Temperate	Tropics	Subtropics	Temperate
			Barley			
Hibernating	n.a.[b]	6.6–14.2	7.4–13.5	n.a.	4.6–10.2	5.2–9.7
Nonhibernating	4.7–9.9	5.2–9.2	3.9–7.6	2.9–6.7	2.9–6.4	2.8–5.1
			Corn			
Grain	6.0–15.6	8.5–17.1	8.0–15.7	3.5–10.5	5.3–12.2	4.9–11.3
Silage	n.a.	17.0–26.0	15.9–24.0	n.a.	13.0–20.9	12.1–19.2
			Cotton			
All	1.1–1.6	1.2–1.6	1.2–1.5	0.7–1.0	0.8–1.0	0.7–0.9
			Peanut			
All	3.1–4.7	3.2–4.9	3.1–4.6	2.0–3.1	2.0–3.3	2.0–3.0
			Rice			
Wetland	7.9–12.2	8.7–12.7	8.2–10.9	6.1–9.5	6.5–9.9	6.3–8.7
Dry land	4.8–6.8	n.a.	n.a.	3.1–4.6	n.a	n.a.
			Sorghum			
All	3.4–12.1	7.8–13.0	5.9–10.3	2.2–7.5	4.6–8.1	3.4–6.4
			Soybean			
All	3.1–4.8	4.6–5.5	4.3–5.1	2.0–3.2	3.0–3.6	2.8–3.4
			Sugar Beet			
All	n.a.	7.1–9.3	6.7–8.6	n.a.	4.8–6.7	4.6–6.2
			Wheat			
Hiberating	n.a.	6.6–14.2	7.4–13.5	n.a	4.6–10.2	5.2–9.7
Nonhiberating	5.3–11.1	5.4–9.9	5.3–8.5	3.3–7.4	3.4–6.9	3.3–5.7

[a] Figures represent yields attained during the cultivation phase of cultivation–fallow cycles. In low and intermediate input agriculture, fallow and/or crop rotations are needed to maintain soil nutrient balance and break pest and disease cycles. The required intensity of fallow depends on crop rotations, soil characteristics such as nutrient availability and retention capacity, climatic conditions, and management and agricultural inputs. As a rule, for intermediate level input and management conditions, fallow requirements may vary from 10 to 30%.
[b] n.a. = not applicable.

Source: Food & Agriculture Organization of the United Nations, Rome, 2001.

1.3 GRAIN CROP STATISTICS

TABLE 1.2
Annual Changes (%) in World Grain Yields by Decade, 1950–1995 (3-year average)

Years	Total Grain	Rice	Wheat	Corn	Other Grains
1950–1960	2.0	1.4	1.7	2.6	—
1960–1970	2.5	2.1	2.9	2.4	2.3
1970–1980	1.9	1.7	2.1	2.7	0.4
1980–1990	2.2	2.4	2.9	1.3	1.7
1990–1995	0.7	1.0	0.1	1.7	-0.8

Source: U.S. Department of Agriculture, unpublished data, 1996.

TABLE 1.3
U.S. Total Grain Supply and Disappearance (million metric tons), 1991–1999[a]

	Supply				Disappearance			
Year[b]	Beginning Stocks	Production	Imports	Total	Domestic Use	Exports	Total Disappearance	Ending Stocks
1990	61.4	312.1	2.8	376.3	219.9	03.9	303.8	72.5
1991	72.5	279.7	3.8	358.0	220.2	87.8	307.9	48.2
1993	79.3	258.8	7.3	345.4	224.2	77.2	301.4	44.0
1994	44.0	355.6	6.3	405.9	246.1	99.2	345.3	80.5
1995	80.5	277.3	5.0	342.9	216.5	100.6	317.1	25.8
1998	25.8	335.5	5.9	367.2	244.5	82.4	326.9	40.3
1997	40.3	338.3	5.9	382.5	245.9	77.5	323.4	59.1
1998	59.1	349.2	6.4	414.6	248.2	88.2	336.5	78.1
1999[c]	78.1	335.1	5.8	419.0	253.0	90.1	343.1	76.0

[a] Aggregate data on corn, sorghum, barley, oats, wheat, rye, and rice.

[b] The marketing year for corn and sorghum begins September 1; for oats, barley, wheat, and rye, June 1; and for rice, August 1.

[c] Preliminary totals may not add due to independent rounding.

Source: Economics Research Service, Washington, D.C., 2001. With permission.

TABLE 1.4
U.S. Total and Per Capita Civilian Consumption of Wheat and Wheat Products, 1990–1999

Calendar Year[a]	Total Consumed (million bushels)[b]	Per Capita Consumption of Flour (pounds)[c]	Per Capita Consumption of Cereal (pounds)
1990	773	136	4.3
1991	791	137	4.5
1992	817	139	4.7
1993	853	143	5.0
1994	871	144	5.2
1995	858	142	5.4
1996	896	149	5.4
1997	902	150	5.4
1998	911	148	5.4
1999	919	147	5.3

[a] Data shown for marketing year (calendar year for wheat).
[b] Excludes quantities used in alcoholic beverages.
[c] Includes white, whole wheat, and semolina flour.

Source: Economics Research Service, Washington, D.C., 2001. With permission. All figures are estimates based on data from private industry sources, U.S. Department of Commerce, Internal Revenue Service, and other government agencies.

TABLE 1.5
U.S. Total and Per Capita Civilian Consumption of Rye and Milled Rice, 1990–1999

Calendar Year[a]	Total Rye Consumed (million bushels)	Per Capita Consumption of Rye Flour (million pounds)	Total Milled Rice Consumed (cwt)	Per Capita Consumption of Rice (pounds)
1990	3.5	0.8	42.7	17.0
1991	3.5	0.6	43.7	17.2
1992	3.5	0.6	45.4	17.7
1993	3.3	0.6	49.6	19.1
1994	3.6	0.6	51.5	19.7
1995	3.2	0.5	52.6	19.9
1996	3.5	0.6	53.7	20.1
1997	3.3	0.5	55.0	20.4
1998	3.7	0.6	56.8	20.9
1999	3.5	0.6	59.3	21.6

[a] Does not include shipments to U.S. territories or rye used in alcoholic beverages; includes imports and rice used in processed foods and pet foods. Calendar year is marketing year for rye; marketing year for rice is August 1 to July 31.

Source: Economics Research Service, Washington, D.C., 2001. With permission. All figures are estimates based on data from private industry sources, U.S. Department of Commerce, Internal Revenue Service, and other government agencies.

TABLE 1.6
U.S. Total and Per Capita Civilian Consumption of Corn and Corn Products, 1990–1999

Calendar Year[a]	Total Consumed (million bushels)[b]	Per Capita Consumption of				
		Flour and Meal (pounds)	Hominy and Grits (pounds)	Syrup (pounds)	Sugar (pounds)	Starch (pounds)
1990	736	14.4	2.9	67.3	3.8	4.0
1991	763	14.9	2.8	72.0	3.9	4.0
1992	791	15.4	2.6	72.9	3.9	4.2
1993	834	15.8	3.1	76.2	3.9	4.4
1994	868	16.1	3.6	78.4	3.9	4.6
1995	895	16.4	4.1	80.2	4.0	4.8
1996	939	18.8	4.6	82.0	4.0	5.0
1997	968	17.1	5.0	85.9	3.8	4.9
1998	976	17.4	5.5	87.3	3.7	4.8
1999[c]	990	17.7	5.9	88.0	3.6	4.8

[a] Data shown for marketing year for corn: September 1 to August 31; marketing years for syrup and sugar are calendar years.
[b] Includes an allowance for quantities used as hominy and grits; series not adjusted for trade.
[c] Preliminary; estimates of corn syrup and sugar are unofficial; industry data not reported after April 1968.

Source: Economics Research Service, Washington, D.C., 2001. With permission. All figures are estimates based on data from private industry sources, U.S. Department of Commerce, Internal Revenue Service, and other government agencies.

TABLE 1.7
U.S. Total and Per Capita Civilian Consumption of Oats and Barley, 1990–1999

Calendar Year[a]	Total Oats Consumed (million bushels)[b]	Per Capita Consumption of Oat Food Products (pounds)	Total Barley Consumed (million bushels)[c]	Per Capita Consumption of Barley Food Products (pounds)[d]
1990	75.3	6.5	6.4	0.8
1991	76.6	6.5	6.0	0.7
1992	77.4	6.5	6.1	0.7
1993	73.0	6.1	6.2	0.7
1994	70.0	5.8	6.3	0.7
1995	67.0	5.5	6.4	0.7
1996	63.0	5.1	6.5	0.7
1997	59.0	4.7	6.9	0.8
1998	59.0	4.5	7.0	0.8
1999	58.8	4.5	7.0	0.8

[a] Calendar year for oats and barley is June 1 to May 3.
[b] Oats used in oatmeal, prepared breakfast foods, infant foods, and food products.
[c] Malt for breakfast and other food uses, pearl barley, and flour.
[d] Malt equivalents of barley food products.

Source: Economics Research Service, Washington, D.C., 2001. With permission. All figures are estimates based on data from private industry sources, U.S. Department of Commerce, Internal Revenue Service, and other government agencies.

TABLE 1.8
North American Verifiable Record Crop Yields

Crop	Yield	Location	Year
Alfalfa	24.1 tons	Arizona	1982
Barley, spring	190 bu/acre	Alberta	1990
Canola, spring	70 bu/acre	Alberta	1999
Corn	393.7 bu/acre	Iowa	1999
Cotton	5.4 bales/acre	Arizona	1982
Soybean	118 bu/acre	New Jersey	1983
Wheat, winter	205 bu/acre	British Columbia	1988

TABLE 1.9
U.S. Average Crop Yields, 2000

Crop	Yield
Corn	137.1 bu/acre
Cotton	631.0 lb/acre
Grain sorghum	60.9 bu/acre
Peanuts	2,499 lb/acre
Rice	6,278 lb/acre
Soybean	36.1 bu/acre
Sugar beet	23.6 tons/acre
Wheat, winter	41.9 bu/acre

1.4 WORLD OIL SEED PRODUCTION

TABLE 1.10
World Oilseed Production, 1999

Crop	Percent (%)	Weight (million short tons)
Soybeans	52	171
Rape seeds	14	46.5
Cotton seeds	11	37.1
Peanuts	10	31.6
Sunflower seeds	9	29.6
Copra	2	5.6
Palm Kernels	2	6.9

1.5 FERTILIZER APPLICATION AND UTILIZATION

TABLE 1.11
Field Crops: Percent of Acreage Receiving Fertilizer Applications, 1995–1999[a]

Crop	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
	1995		
Corn	97	81	70
Cotton, upland	87	56	40
Soybeans	17	22	25
Wheat, winter	86	54	16
Wheat, durum	92	78	10
Wheat, other spring	87	78	23
	1996		
Corn	98	85	73
Cotton, upland	77	55	43
Soybeans	15	25	27
Wheat, winter	86	51	6
Wheat, durum	93	73	8
Wheat, other spring	89	79	24
	1997		
Corn	99	84	72
Cotton, upland	90	67	58
Soybeans	20	26	33
Wheat, winter	84	53	15
Wheat, durum	95	77	8
Wheat, other spring	92	82	25
	1998		
Corn	98	63	66
Cotton, upland	84	66	53
Soybeans	17	24	27
Wheat, winter	89	63	22
Wheat, durum	94	76	5
Wheat, other spring	87	77	25
	1999		
Corn	98	82	67
Cotton, upland	86	59	52
Soybeans	18	26	28

[a] Acres receiving one or more applications of specific fertilizer ingredient.

Source: Economics and Demographics Branch, National Agricultural Statistics Service, Washington, D.C., 2001. All states surveyed.

TABLE 1.12
Nutrient Utilization (lb/acre) by Various Agronomic Crops

Yield	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)	Magnesium (Mg)	Sulfur (S)
			Corn		
100 bu/acre	150	60	125	30	18
150 bu/acre	220	80	195	40	25
180 bu/acre	240	100	240	50	30
200 bu/acre	266	114	266	65	33
			Cotton		
1000 lb/acre	149	51	112	32	28
2000 lb/acre	180	63	126	35	30
			Oats		
100 bu/acre	115	40	145	20	19
			Grain Sorghum		
8000 lb/acre	250	90	240	44	38
			Peanuts		
4000 lb/acre	240	39	185	25	21
			Rice		
7000 lb/acre	112	60	168	14	12
			Soybeans		
40 bu/acre	224	53	97	18	17
60 bu/acre	324	64	142	27	25
			Sugar Beets		
30 tons/acre	255	40	550	80	45
			Wheat		
40 bu/acre	160	54	184	24	20

TABLE 1.13
Uptakes of Major Elements and Micronutrients by Various Agronomic Crops

Crop and Yield	Nitrogen (kg)	Phosphate (kg)	Potash (kg)	Calcium (kg)	Magnesium (kg)	Sulfur (kg)	Boron (g)	Copper (g)	Iron (g)	Manganese (g)	Molybdenum (g)	Zinc (g)
Alfalfa (18 tons/acre)	500	134	538	218	50	50	600	120	1200	600	24	830
Corn (10 tons/acre)	240	102	120	43	58	30	36	20	120	36	—	60
Cotton lint (1.7 tons/acre)	200	57	95	14	23	20	120	110	140	190	2	480
Peanuts (4.5 tons/acre)	270	45	92	20	25	21	—	60	480	400	—	—
Rice (7.8 tons/acre)	125	67	130	23	16	21	60	20	810	600	2	215
Soybeans (4.0 tons/acre)	350	65	180	29	27	22						
Wheat (4.0 tons/acre)	130	46	180	18	20	17	36	43	380	120	—	180

Source: *International Soil Fertility Manual*, Potash & Phosphate Institute, Norcross, GA, 1995. With permission.

1.6 WEIGHTS AND MEASURES

TABLE 1.14
Weights and Measures of Agronomic Commodities

Commodity	Unit	Approximate Net Weight (lb)	Approximate Net Weight (kg)
Alfalfa	bu	60	27.2
Barley	bu	48	21.8
Corn ear, husked	bu	70	31.8
Corn, shelled	bu	56	25.4
Corn meal	bu	50	22.7
Corn oil	gal	7.7	3.5
Cotton	bale, gross	500	227
Cotton	bale, net	480	218
Cottonseed	bu	32	14.5
Cottonseed oil	gal	7.7	3.5
Oats	bu	32	14.5
Peanut oil	gal	7.7	3.5
Peanut runners	bu	21	9.5
Peanuts, Spanish	bu	25	11.3
Peanuts, unshelled Virginia	bu	17	7.7
Rice, milled	bag	100	45.4
Rice, rough	bag	100	45.4
Rice, rough	barrel	162	73.5
Rice, rough	bu	45	20.4
Sorghum, grain	bu	56	25.4
Soybean oil	gal	7.7	3.5
Soybeans	bu	60	27.2
Wheat	bu	60	27.2

Source: U.S. Department of Agriculture, *Agricultural Statistics, 2001*. U.S. Government Printing Office, Washington, D.C.

TABLE 1.15
Weights of Full Bushels and Standard Yields of Grain

Weight/bu (lb)	Wheat, Beans, and Soybeans[a]	Flax, Shelled Corn, Sorghum, and Rye[a]	Barley[a]
64	1.07	—	—
62	1.03	—	—
60	1.00	1.07	—
58	0.97	1.04	—
56	0.93	1.00	—
54	0.90	0.96	—
52	0.87	0.93	1.08
50	0.83	0.89	1.04
48	0.80	0.86	1.00
46	0.77	0.82	0.96
44	0.73	0.79	0.92
42	0.70	0.75	0.87
40	0.67	0.71	0.83

[a] Numbers in columns denote multiplication factors required to determine standard bushels.

TABLE 1.16
Conversion Factors for Agronomic Crops

Crop	Unit	Approximate Equivalent
Corn, shelled	1 bu (56 lb)	2 bu (70 lb) husked ears
Cotton	1 bu ginned	3.26 lb seed cotton including trash
Peanuts	1 lb shelled	1.5 lb unshelled
Rice, milled	100 lb	152 lb rough or unhulled grains
Soybean meal	1 lb	1.27 lb soybeans
Soybean oil	1 lb	5.49 lb soybeans
Sugar	1 ton raw	0.9346 ton refined
Wheat flour	100 lb	2.30 bu wheat

TABLE 1.17
Crop Seeds per Pound, Weights per Bushel, and Germination Times

Crop	No. seeds/lb (1,000)	No. of seeds/g	Weight/bu (lb)	Germination Time (days)
Alfalfa	220	500	60	7
Barley	13	30	48	7
Corn	62	3	56	7
Cotton	4	8	—	12
Oats	14	30	32	10
Peanut	1	1–3	20–30	10
Rice	15	65	45	14
Sorghum	15	33	56	10
Soybean	2–3	6–13	60	8
Sugar beet	22	48	15	—
Wheat	12–20	35	60	7

1.7 NUTRIENT VALUES OF GRAIN AND OIL SEEDS

TABLE 1.18
Comparison of the Nutritive Values of Selected Grain and Oilseed Crops

Crop	Calories /100 g	Protein (%)	Fat (%)	Ca (mg/lb)	P (mg/lb)	K (mg/lb)	Carboh-drates (%)
Barley, pearled	349	8.2	1.0	16	189	160	78.8
Corn, whole ground	355	9.2	3.9	20	256	284	73.7
Rice, milled	363	6.7	0.2	24	94	92	80.4
Rye, whole grain	334	12.1	1.7	38	376	467	73.4
Sorghum, whole grain	332	11.0	3.3	28	287	350	73.0
Peanut, whole seed	564	26.0	47.5	69	401	674	18.6
Soybean, whole seed	403	34.1	17.7	226	554	1,677	33.5

Source: *Handbook of the Nutritional Contents of Foods*, 1975, Dover Publications, Inc., New York. With permission.

TABLE 1.19
Quality Components of Grains

Component	Sorghum	Corn	Barley	Wheat
Digestible energy (kcal/kg)	3,453	3,610	3,080	3,520
Protein (%)	11.0	10.0	11.6	13.7
Lysine (%)	0.27	0.13	0.53	0.45
Methionine + cystine (%)	0.27	0.18	0.36	0.36
Tryptophan (%)	0.09	0.09	0.18	0.18
Calcium (%)	0.04	0.01	0.08	0.05
Phosphorus (%)	0.30	0.31	0.42	0.36
Fiber (%)	2.0	2.0	5.0	3.0
Ether extract (%)	2.8	3.9	1.9	1.7

1.8 NITROGEN FIXATION OF LEGUME CROPS

TABLE 1.20
Nitrogen Fixation Rates of Legume Crops

Crop	Nitrogen (kg/ha)
Alfalfa	150
Sweet clover	120
Red clover	90
Soybean	60

REFERENCES

1. Gardner, G., 1996, *Shrinking Fields: Cropland Loss in a World of Eight Billion*, Worldwatch Paper 131, Worldwatch Institute, Washington, D.C.
2. *Vital Signs 2001: The Trends that Are Shaping Our Future*, Worldwatch Institute, Washington, D.C.

2 Grain Crops

2.1 BARLEY (*Hordenum vulgare* L.)

2.1.1 Introduction

Barley is one of the world's oldest crop plants. While its origins are unknown, humans may have consumed it as early as 15,000 B.C. It was farmed in China around 7,000 B.C., in Spain by 5,000 B.C., and in England by 3,000 B.C. It belongs to the same plant family (Poaceae or Gramineae) as corn, oats, rice, and wheat, and is grown primarily for malting grain and as livestock feed. Barley grows throughout the Temperate Zone. It thrives in cool northern climates and at high altitudes, and is planted in warmer climates as a winter crop.

Barley is planted in rows 6 to 7 in. (15 to 18 cm) apart and seeds at a rate of 1 to 2 bu per acre (2.5 to 5 bu per ha). In the U.S., barley area seeded in 2001 totalled 5.09 million acres — down 13% from the 5.84 million acres seeded in 2000. The yield averages about 60 bu per acre (149 bu per ha). The highest worldwide yields range from 108 to 116 bu per acre (267 to 287 bu per ha). Annual world production is about 7.75 billion bu; 1 bu weighs 48 lb (22 kg).

In the U.S., 55% of produced barley grain is used as animal feed and high quality barley is made into malt for use in beer, liquor, malted milk, and flavorings. In 1990, the highest verifiable barley grain yield of 190 bu per acre was recorded in Alberta, Canada. In the U.S. in 2000, the average barley yield was 61.1 bu per acre.

2.1.2 Production Statistics

TABLE 2.1
U.S. Barley Area, Yield, and Production, 1991–2000

Year	Area Harvested (1,000 acres)	Yield (bu/acre)	Production (1,000 bu)
1991	8,413	55.2	464,326
1992	7,285	62.5	455,090
1993	6,753	58.9	398,041
1994	6,667	56.2	374,862
1995	6,279	57.2	359,376
1996	6,707	58.5	392,433
1997	6,198	58.1	359,878
1998	5,864	60.0	352,125
1999	4,734	59.2	280,292
2000[a]	5,201	61.1	317,865

[a] Preliminary.

Source: Crops Branch, National Agricultural Statistics Service, Washington, D.C.

TABLE 2.2
Leading Barley-Growing Countries, 1999–2000

Country	1,000 Metric Tons
Germany	13,301
Canada	13,196
Russia	10,600
France	9,539
Spain	7,434
Turkey	6,600
United Kingdom	6,580
Ukraine	6,400
United States	6,103
Denmark	3,620
China	3,000
Kazakhstan	2,250

Source: Foreign Agriculture Service, Washington, D.C., 2001.

TABLE 2.3
Leading Barley-Producing States, 2000

State	Area Harvested	Yield/Harvested Acres	Production (1,000 bu)
North Dakota	1,770	55.0	97,350
Montana	950	50.0	38,000
Idaho	730	76.0	55,480
Washington	490	70.0	34,300
Minnesota	240	64.0	15,360
U.S. Total	5,201	61.1	317,865

Source: Crops Branch, National Agricultural Statistics Service, Washington, D.C., 2001.

TABLE 2.4
U.S. Total and Per Capita Civilian Consumption of Barley and Barley Products as Food, 1990–1999

Calendar Year[a]	Total Consumed (million bu)[b]	Per Capita Consumption of Food Products (lb)[c]
1990	6.4	0.8
1991	6.0	0.7
1992	6.1	0.7
1993	6.2	0.7
1994	6.3	0.7
1995	6.4	0.7
1996	6.5	0.7
1997	6.9	0.8
1998	7.0	0.8
1999[d]	7.0	0.8

[a] Data for marketing year, June 1 to May 3.
[b] Malt for breakfast and other food uses, pearl barley, and flour.
[c] Malt equivalent of barley food products.
[d] Preliminary.

Source: Economics Research Service, Washington, D.C., 2001. With permission. All figures are estimates based on data from private industry sources, the U.S. Department of Commerce, the Internal Revenue Service, and other government agencies.

2.1.3 Barley Grain Composition

TABLE 2.5
Quality Components of Barley Grain

Component	Value
Digestable energy (kcal/kg)	3,080
Protein (%)	11.6
Lysine (%)	0.53
Methionine + cystine (%)	0.36
Tryptophan (%)	0.18
Calcium (%)	0.08
Phosphorus (%)	0.42
Fiber (%)	5.0
Ether extract (%)	1.9

Source: *Principles of Field Crop Production*, 3rd ed., 1976, Macmillan, New York. With permission.

TABLE 2.6
Nutritive Values of Pearled Barley Grain

Component	Value
Calories/100 g	349
Protein, %	8.2
Fat, %	1.0
Total calcium, mg/lb	16
Total phosphorus, mg/lb	189
Total potassium, mg/lb	160
Carbohydrates, %	78.8

2.1.4 Plant Analysis Interpretation

TABLE 2.7
Nutrient Element Sufficiency Ranges[a]

Nutrient Element	Sufficiency Range
Nitrogen	1.75–3.00%
Phosphorus	0.20–0.50%
Potassium	1.50–3.00%
Calcium	0.30–1.20%
Magnesium	0.15–0.50%
Sulfur	0.15–0.40%
Copper	5–25 ppm
Manganese	25–100 ppm
Molybdenum	0.11–0.18 ppm
Zinc	15–70 ppm

[a] Twenty-five whole plants measured from emergence of head to boot.

Source: Plant Analysis II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide, 1996, MicroMacro Publishing, Athens, GA. With permission.

2.1.5 Barley Grading and Glossary

2.1.5.1 Terms Used by the U.S. Department of Agriculture Federal Grain Inspection Service (USDA-FGIS) to Grade Barley[1]

2.1.5.1.1 Definition of Barley

Grain that, before the removal of dockage, consists of 50% or more of whole kernels of cultivated barley (*Hordeum vulgare* L.) and not more than 25% of other grains for which standards have been established under the U.S. Grain Standards Act. The term *barley* as used in the standards does not include hull-less barley or black barley. The term *barley* also covers kernels that do not meet the requirements for six-row and two-row barley cited below.

2.1.5.1.2 Black Barley

Barley with black hulls.

2.1.5.1.3 Broken Kernels

Barley with more than one-fourth of the kernels removed.

2.1.5.1.4 Classes of Barley

The three classes are six-row barley, two-row barley, and barley.

2.1.5.1.4.1 Six-Row Barley

Six-row barley has white hulls and contains not more than 10% of two-row barley. Six-row barley is divided into three subclasses:

Six-row malting barley — Six-row barley of a suitable malting type that has 90% or more kernels with white aleurone layers; contains not more than 1.9% injured-by-frost kernels that may include not more than 0.4% frost-damaged kernels; is not more than 0.2% injured-by-heat kernels that may include not more than 0.1% heat-damaged kernels; is not blighted, ergoty, garlicky, infested, or smutty; and otherwise meets the grade requirements of the six-row mating barley subclass; may contain unlimited amounts of injured-by-mold kernels. Mold-damaged kernels are scored as damaged kernels and against sound barley limits.

Six-row blue malting barley — Six-row barley of a suitable malting type that has 90% or more kernels with blue aleurone layers; contains not more than 1.9% injured-by-frost kernels that may include not more than 0.4% frost-damaged kernels; is not more than 0.2% injured-by-heat kernels that may include not more than 0.1% heat-damaged kernels; is not blighted, ergoty, garlicky, infested, or smutty; and otherwise meets the grade requirements of the six-row blue malting barley subclass; may contain unlimited amounts of injured-by-mold kernels. Mold-damaged kernels are scored as damaged kernels and against sound barley limits.

Six-row barley — Any barley of the class six-row type that does not meet the requirements of the six-row malting or six-row blue malting barley subclasses.

2.1.5.1.4.2 Two-Row Barley

Barley of the two-row type has white hulls and contains not more than 10% of six-row barley. This class is divided into two subclasses:

Two-row malting barley — Two-row barley of a suitable malting type that contains not more than 1.9% injured-by-frost kernels that may include not more than 0.4% frost-damaged kernels; is not more than 1.9% injured-by-mold kernels that may include not more than 0.4% mold-damaged kernels; is not more than 0.2% injured-by-heat kernels that may include not more than 0.1% heat-damaged kernels; is not blighted, ergoty, garlicky, infested, or smutty; and otherwise meets the grade requirements of the two-row malting barley subclass. Injured-by-frost kernels and injured-by-mold kernels are not scored against sound barley

Two-row barley — Two-row barley that does not meet the requirements of the two-row malting barley subclass.

2.1.5.1.5 Damaged Kernels

Kernels, pieces of kernels, other grains, and wild oats that are badly ground-damaged, badly weather-damaged, diseased, frost-damaged, germ-damaged, heat-damaged, heat-injured, insect-bored, mold-damaged, sprout-damaged, or otherwise materially damaged.

2.1.5.1.6 Dockage

All matter other than barley that can be removed from the original sample by use of an approved device according to FGIS instructions. Also, under-developed, shriveled, and small pieces of barley kernels removed in properly separating the material other than barley and that cannot be recovered by properly rescreening or recleaning.

2.1.5.1.7 Foreign Material

All matter other than barley, other grains, and wild oats that remains in a sample after removal of dockage.

2.1.5.1.8 Frost-Damaged Kernels

Barley kernels, pieces of kernels, other grains, and wild oats that are badly shrunken and distinctly discolored black or brown by frost.

2.1.5.1.9 Germ-Damaged Kernels

Barley kernels, pieces of kernels, other grains, and wild oats that have dead or discolored germ ends.

2.1.5.1.10 Heat-Damaged Kernels

Barley kernels, pieces of kernels, other grains, and wild oats that are materially discolored and damaged by heat.

2.1.5.1.11 Injured-by-Frost Kernels

Barley kernels and pieces that are distinctly indented, immature, or shrunken in appearance or are light green in color as a result of frost before maturity.

2.1.5.1.12 Injured-by-Heat Kernels

Barley kernels, pieces of kernels, other grains, and wild oats that are slightly discolored as a result of heat.

2.1.5.1.13 Injured-by-Mold Kernels

Barley kernels and pieces containing slight evidence of mold.

2.1.5.1.14 Mold-Damaged Kernels

Barley kernels, pieces of kernels, other grains, and wild oats that are weathered and contain considerable evidence of mold.

2.1.5.1.15 Other Grains

Black barley, corn, cultivated buckwheat, einkorn, emmer, flaxseed, guar, hull-less barley, nongrain sorghum, oats, Polish wheat, popcorn, poulard wheat, rice, rye, safflower, sorghum, soybeans, spelt, sunflower seed, sweet corn, triticale, and wheat.

2.1.5.1.16 Plump Barley

Barley that remains on top of a 6/64 × 3/4 slotted-hole sieve after sieving according to FGIS instructions.

2.1.5.1.17 Sieves

1. 4/64 by 3/4 slotted-hole sieve. A metal sieve 0.032 in. thick with slotted perforations 0.0781 (5/64) in. by 0.750 (3/4) in.
2. 5.5/64 by 3/4 slotted-hole sieve. A metal sieve 0.032 in. thick with slotted perforations 0.0895 (5.5/64) in. by 0.750 (3/4) in.
3. 6/64 by 3/4 slotted-hole sieve. A metal sieve 0.032 in. thick with slotted perforations 0.0937 (6/64) in. by 0.750 (3/4) in.

2.1.5.1.18 Skinned and Broken Kernels

Barley kernels that have one-third or more of their hulls removed, or with the hull loose or missing over the germ, or broken kernels, or whole kernels that have a part or all of the germ missing.

2.1.5.1.19 Sound Barley

Barley kernels and pieces that are not damaged, as defined under 2.1.5.1.5.

2.1.5.1.20 Stained Barley

Barley that is badly stained or materially weathered.

2.1.5.1.21 Suitable Malting Barley

Varieties of malting barley that are recommended by the American Malting Barley Association as suitable for malting purposes. The recommended varieties are listed in FGIS instructions.

2.1.5.1.22 Thin Barley

Six-row barley that passes through a 5/64 by 3/4 slotted-hole sieve and two-row barley that passes through a 5.5/64 by 3/4 slotted-hole sieve after sieving according to FGIS instructions.

2.1.5.1.23 Wild Oats

Seeds of *Avena fatua* L. and *Avena sterilis* L.

2.1.5.1.24 All Other Determinations

Each determination of heat-damaged kernels, heat-injured kernels, and white or blue aleurone layers in six-row barley is made on pearled, dockage-free barley. Other determinations not specifically provided for under the general provisions are made on the basis of the grain when free from dockage, except that determination of odor is made on the basis of either the grain as a whole or the grain free from dockage.

2.1.5.1.25 Special Grades and Special Grade Requirements

1. Blighted — barley that contains more than 4% fungus-damaged and/or mold-damaged kernels.
2. Ergoty — barley that contains more than 0.10% ergot.
3. Garlicky — barley that contains three or more green garlic bulblets, or an equivalent quantity of dry or partly dry bulblets per 500 g barley.
4. Smutty — barley that has kernels covered with smut spores to give a smutty appearance or contains more than 0.20% smut balls.

2.1.5.2 Barley Glossary[1]

Acrospire Shoot formed in the germination process that grows to about the length of the kernel. The part that extends from under the hull is broken off and along with the rootlet becomes a feed by-product.

Aleurone The barley kernel is composed of the lemma and palea, a short portion of the rachilla, and the caryopsis. The seed coat of the caryopsis contains a few layers of important nitrogen-rich cells comprising the aleurone layer. These cells, when properly activated, secrete hydrolytic enzymes into the endosperm that disintegrate the structures of the starch-containing storage materials and accomplish what is called "modification."

Country elevator A facility located in a production area that serves as a primary outlet for off-farm sales. Country elevators unofficially determine grain grades and weights. They generally take title to the grain they handle, and may handle grain previously contracted to another buyer.

Dense barley Barley with short rachis internodes that give the inflorescence a dense or compact appearance.

Enzyme potential Barley, when malted, produces two known starch-splitting enzymes designated alpha amylase and beta amylase. The combination of the two enzymes results in more rapid and complete hydrolysis of starch to dextrin and fermentable sugars. Only barley, wheat, and rye contain both alpha and beta enzymes. The potential for transforming starch to fermentable sugars is not the same for all varieties so malt varieties are carefully selected.

Facultative winter barley Winter barley requires little cold temperature for vemalization and may reproduce when spring-planted, unlike the obligate winter type that requires longer periods of cold temperatures to initiate flowering.

High grading Process that separates low- and high-quality products. Poorer quality barley kernels unsuitable for malting are separated and sold to feed manufacturers, leaving a higher quality malting product.

Hooded barley The inflorescence has a modified lemma awn that resembles a heal over the floret. Hoods may have both male and female organs and in rare instances produce viable seeds.

Hull-less barley The hulls of this barley trash free of the caryopsis during harvest. Most U.S. barley cultivars are not hull-less.

Inland terminal elevator A facility located at a point of accumulation and distribution in the movement of grain. An inland terminal elevator procures a large share of its grain from other elevators rather than directly from farmers. These elevators have facilities for establishing official grades and weights and may store grain for others.

Kilning Drying malted barley with hot, dry air in a kiln or oven.

Lax barley Barley with long rachis internodes that give the inflorescence an open lax appearance.

Malt Final product after kilning. It is cleaned to remove the dried rootlets and given a degree of polishing; it may be called final malt. Casual observation indicates that the final product varies little in appearance from the original barley, but close inspection reveals that the kernels are somewhat larger, the dried acrospires noticeably budge under the husks, and husks do not adhere as tightly to the main bodies of the kernels.

Malt sprouts Rootlets separated from malt before kilning. Malt sprouts average about 27% protein, 2.5% fat, and 12% fiber. They are commonly used in dairy feeds.

Midwestern six-row Manchurian Relatively small kerneled barleys with medium-high protein content that germinate vigorously and produce high enzymatic activities during malting; used to produce brewers' and distillers' malts.

Modification The limited breakdown of the starch endosperms of barley by enzymes during the germination phase of malting. Modified starch is readily converted to dextrin and fermentable sugars when ground and mixed with water to 60 to 70°F.

Naked barley Hull-less barley.

No-row barley The axis of the barley head has nodes along its length. Spikelets at these nodes alternate from side to side. For two-row barley, only the central kernel develops (both laterals are sterile; *cf.* six-row barley.

Pearled barley Barley product remaining after the hull, the kernel coating most of the embryo, and part of the outer layers of the starchy endosperm are removed by a grinding process[1] 100 lb high grade yields approximately 35 lb pearled barley.

Pipeline stocks The grains or grain products that are not in storage awaiting a buyer or in inventory as stored grain. They may be in transit or may be held in working space.

Port terminal elevator An elevator located along a waterway and designed to load vessels with grain and other products. A port terminal elevator receives most of its grain from subterminal elevators or inland terminals. Port terminals have facilities for establishing official grades and weights.

Rachilla An inconspicuous pedicel or branch attached to the rachis and to which the florets are attached.

Six-row barley The axis of the barley head has nodes along its length. Spikelets at these nodes alternate from side to side. For six-row barley, three kernels develop at each node (one central kernel and two lateral kernels).

Spent grain Hulls and other solids remaining in the brewers mash tub. Spent grains are dried and sold as feed by-products.

Terminal market A large concentration of wholesale grain handlers, commission merchants, and grain brokers that may be complemented by a grain exchange or board of trade that

houses an association organized for the purpose of providing a place where buyers and sellers may conduct trading in both the cash and futures markets.

True winter type Barley requiring a prolonged period of cold for vernalization; usually will not flower when spring-planted.

Vernalization The stimulation of reproductive growth of a plant by passing it through a period of temperatures below 50°F. A true winter barley, for example, will not mature if planted in the spring and exposed to temperatures above 50°F. Duration of vernalization is cultivar- and temperature-dependent.

Western six-row Brewing barley grown primarily in California. Large, hulled kernels, medium protein content, rather slow physical and chemical modification potential, and low enzymatic activities after malting are the characteristics of this type. It is used for brewing on the West Coast and in Rocky Mountain areas and for blending with midwestern brewing malts.

Western two-row Grown primarily in the Northwest and intermountain areas of the U.S., this type has medium-sized, uniform, plump kernels with thin hulls. The type is generally low in protein and high in starch and exerts vigorous germination and intermediate enzymatic activity during mating; used by the brewing industry alone and blended with midwestern six-row barley.

2.1.6 Weights and Measures

The net weight of one bushel of barley grain is approximately 48 lb or 21.8 kg.

TABLE 2.8
Barley Seeds/Pound, Weight/Bushel, and Germination Time

Seeds (1,000/lb)	No. Seeds/g	Weight (lb/bu)	Germination Time (days)
13	30	48	7

TABLE 2.9
Weight and Standard Yield of Full (Level) Bushel of Barley Grain

Weight of 1 bu (measured)	Multiplication factor to yield standard bushels (lb)
52	1.08
50	1.04
48	1.00
46	0.96
44	0.92
42	0.87
40	0.83

REFERENCES

1. Smith, C.W., *Crop Production: Evolution, History, and Technology*, 1995, John Wiley & Sons, New York.

2.2 CORN (*Zea mays* L.)

2.2.1 Introduction

Corn (known as mais in France, Germany, and Italy and maiz in Spain) belongs to the Poaceae or Gramineae grass family. It is a cereal grass grown in more countries than any other crop and is the most important crop grown. It has a wide variety of food uses and ranks second (after wheat) in world grain production. The kernels can be eaten directly and used as components of many food products. Kernels and plants are used as livestock feed. Yellow dent is used primarily as livestock feed; white dent is used for human consumption as meal and cereals. Corn is also used in the manufacture of nonfood products including ceramics, drugs, paints, paper goods, and textiles.

In developing countries in Latin America, Africa, and Asia, corn forms a major part of human diets. Corn kernels are rich in starch carbohydrates. They contain small quantities of fats and proteins but lack some important amino acids. Therefore, diets based primarily on corn-based foods can lead to protein malnutrition if other sources of protein are not added to diets.

Corn has been used as a food for over 10,000 years. Indians first gathered it from wild plants in Mexico. They learned how to grown corn around 5000 B.C. By the late 1500s, corn was a well established crop in Africa, Asia, southern Europe, and the Middle East. It was the basic food in the American Colonies in the 1600s and 1700s.

Corn can be grown in most mild and tropical regions (30 to 55° latitude) — mainly in latitudes below 47°. A warm weather crop, corn grows best when air temperatures range from 21 to 27°C and the optimum mean air temperature is below 19°C. Evapotranspiration ranges from 0.20 to 0.25 cm per day for young plants and up to 0.48 cm per day during the reproduction stage. Corn produces best when rotated with other crops, particularly legumes that can add N to the soil for the next corn crop and reduce the potential for pests and diseases.

Corn can be bred and selected to fit growing seasons with maturities ranging from 60 days to over 40 weeks. Plant densities vary from 15,000 to 25,000 plants per ha, with higher densities up to 75,000 plants per ha in humid or irrigated areas when optimum production is required. Spacing between rows ranges from 50 to 100 cm.

The best plant growth occurs on soils with pH levels from 6.0 to 7.0 and moderate to high fertility. Over half of the N and P and 80% of the K for best growth is required before the reproductive stage. The N requirement for corn planted after a legume crop varies from 45 to 100 kg per ha and, for corn planted after a nonleguminous crop, 145 to 170 kg per ha in the Corn Belt.

Under irrigation, a 50 to 70% portion of the N is preplanted and the remainder is applied in 20 to 25 kg per ha increments through irrigation systems. Fertilizer N rates are frequently adjusted based on yield goal and expected climatic conditions. For P and K, fertilizer rates should be based on soil test recommendations. Based on surveys, PK fertilizer rates range from 54 to 84 kg P_2O_5 per ha and from 56 to 84 kg K_2O per ha. For some soils, B and Zn are included in fertilizer recommendations.

In 1999, the highest verifiable corn grain yield of 393.7 bu per acre was recorded in Iowa. In the U.S. 2000, the average corn grain yield was 137.1 bu per acre.

2.2.2 Kinds of Corn

2.2.2.1 Dent Corn

Dent corn forms when the soft floury starch in the kernels dries and shrinks. Most kernels are yellow or white. Dent corn is most widely grown in North America and is used chiefly for livestock feed and in manufacturing processed foods and industrial products.

2.2.2.2 Flint Corn

Flint corn has hard round kernels with smooth coats. Its color ranges from white to red. It grows well in cool climates and reaches maturity early. It is used for food and livestock feed and grown widely in Asia, Europe, and Central and South America.

2.2.2.3 Flour Corn

Flour corn kernels are white, blue, or variegated. Flour corn is the oldest type; it was grown in central Mexico and western South America more than 5,000 years ago. It is grown primarily for food.

2.2.2.4 Pod Corn

Pod corn is the most primitive and possibly oldest form of corn. Each kernel is enclosed in a pod or husk and the entire ear is surrounded by husk. Pod corn has no commercial value; it is used in scientific research.

2.2.2.5 Popcorn

Popcorn is one of the oldest varieties. The two types are pearl popcorn (kernels are rounded and usually yellow or orange) and rice popcorn (kernels are pointed and white). The kernels have hard endosperms with small amounts of white starch in their centers. Steam is created inside the kernels when they are heated. This causes them to explode, turn inside out, and become light, fluffy masses.

2.2.2.6 Sweet Corn

Sweet corn kernels are soft and may be white or yellow. The kernels are the sweetest and may be eaten directly from cooked cobs or removed from the cobs.

2.2.2.7 Waxy Corn

The endosperm of a waxy kernel has a wax-like appearance. The corn consists mostly of starch (amylopectin). This quality makes it useful as a thickener in instant pudding mixes, gravies, and sauces, and glues.

2.2.3 Corn Glossary

Aflatoxin Any of a number of mycotoxins produced by the *Aspergillus flavus* fungus.

Amylase Enzyme that accelerates the hydrolysis of starch.

Amylopectin Heavy molecular weight component of starch that has a branched structure of glucose subunits. Amylopectin and amylose are the components of corn starch.

Amylose Component of starch; has straight chains of glucose subunits.

Blending Mixing two or more grain lots to establish an overall quality that may or may not be different from any single lot.

Country elevator Grain elevator that serves as the first collection point in the marketing of corn. Grain elevators accept, dry, and store corn from producers. It is then delivered to terminal elevators.

Cultivar (cultivated variety) International term denoting certain cultivated plants that are clearly distinguishable from others by one or more characteristics. A cultivar will retain those characteristics when reproduced.

Dockage Materials such as stems, weeds, dirt, and stones that are removed readily by ordinary grain cleaning equipment; also called foreign material.

Double-cross hybrid Hybrid developed by crossing the F1s of two single cross-hybrids.

Dry milling Process of cleaning, conditioning, grinding, and sifting that separates corn into its germ, bran, and endosperm components.

Embryo Undeveloped plant within a seed.

Endosperm Dead but nutritive tissue in seeds found in the inner bulk of kernel consisting primarily of carhohydrates, but also containing protein, riboflavin, and B vitamins. The endosperm provides nutrients to the seedling plant during germination-emergence and early seedling growth.

Enzyme Group of catalytic proteins produced by living cells that mediate the chemical processes of life without being destroyed or altered.

Federal Grain Inspection Service (FGIS) U.S. Department of Agriculture branch responsible for setting grain standards and developing the technology to measure factors affecting grain quality; also develops sampling and inspection procedures, evaluates and approves equipment monitor inspection accuracy, and oversees mandatory export inspection of grain.

Feed grain Grain characterized as high-energy because of high levels of carbohydrates and low levels of crude fiber.

Germ See *embryo*.

Genotype Hereditary makeup of an individual plant or animal.

Germplasm Genotype of crop species or related species used or of potential use in developing cultivars; also called race stocks, breeding lines, inbred lines, or germplasm lines.

Grain Seed or fruit of various food or feed plants including cereal grains (wheat, corn, barley, oats, and rye) and other plants in commercial and statutory use, such as soybeans.

Hybrid Cultivar resulting from crossing two genetically unlike inbred lines of corn.

Inbred line Parent in the development of a hybrid cultivar developed by repeated generations of self-pollination.

Intrinsic quality Characteristic important to the end use of grain. A characteristic is nonvisual and can only be determined by analytical tests to determine, for example, protein, ash, oil content, or starch.

Millfeed Material remaining after all food-grade flour and other components have been extracted from grain used in animal feed and feed supplements.

Modified single-cross Scheme of hybrid production where the female parent is the F1 from the cross of two genetically similar parents. The F1 is crossed with a genetically dissimilar pollen parent to produce hybrid seed sold to the farmer.

Open pollinated Seed produced on plants or to cultivars maintained with no control over which individual plants pollinate other plants within the seed increase blocks.

Pericarp Seed covering derived from the ovary wall.

Phenotype Plant as seen; the outward expression of the genotype of a plant within the limits of its environment.

Protein Complex organic compound composed of nitrogen (N), carbon (C), hydrogen (H), and oxygen (O) essential to the functionings and structures of all organic cells.

Shrinkage Loss of grain weight due to the removal of water.

Single-cross Production of hybrid cultivars by crossing two genetically dissimilar inbred lines of corn.

Starch Primary fraction of corn endosperm composed of straight and branched chains of glucose molecules. Starch is an important component of animal diets. It reacts with enzymes to form dextrose, maltose, and other sugars required for energy and growth.

Steepwater Water used to soak corn during wet milling.

Tempering Addition of water to corn and wheat during dry milling to aid in removing bran from the endosperm.

Terminal elevator Elevator that takes delivery of corn from country elevators; usually owned by or will sell to a manufacturer of corn products; may sell corn to the export trade or to other terminal elevators.

Three-way cross Hybrid production scheme by which the F1 of two genetically dissimilar inbred lines of corn are crossed with a genetically dissimilar inbred to produce hybrid corn seed.

Variety See *cultivar.*

Wet milling Process of using water in which corn is tempered, steeped, and milled to separate the grain into its germ, hull, gluten, and starch components. Oil is extracted from the germ; the hulls are dried and may be added to gluten to produce corn gluten feed; gluten may be purified and used in several industrial products; and the starch is converted into corn syrups and corn sugars.

TABLE 2.10
Growth Stages of Corn, Cumulative Growing Degree Days, and Calendar Days Required to Reach Successive Stages

State No.	Stage	Stage Description	Growing Degree Days[a]	Calendar Days
0.0	Emergence	Tips of leaves emerged from the coleoptile	120	10
0.5	Two-leaf	Two leaves fully emerged with collars visible	200	17
1.0	Four-leaf	Four leaves fully emerged		
1.5	Six-leaf	Six leaves fully emerged; tassel initiation	475	30
2.0	Eight-leaf	Eight leaves fully emerged; tassel developing rapidly	—	—
2.5	Ten-leaf	Ten leaves fully emerged; tassel developing rapidly; ear shoots developing at 6 to 8 nodes	740	50
3.0	Twelve-leaf	Twelve leaves fully emerged; ears developing rapidly; number of ovules determined	—	—
3.5	Fourteen-ear	Fourteen leaves fully emerged; tassel near full size; 1 to 2 ears developing rapidly; silks developing	1,000	60
4.0.	Sixteen-leaf	Sixteen leaves fully emerged; ears and silks developing rapidly; tassel emerges	1,150	75
5.0	Silking	Leaves and tassel fully emerged; elongation of stem ceases; cob and silks growing rapidly; silks continue to grow until fertilized	1,480	75
6.0	Blister	Cob and husks fully developed; starch begins to accumulate in kernels	—	8
7.0	Dough	Kernels growing rapidly; consistency like bread dough	1,925	95
8.0	Beginning dent	A few kernels showing dents	—	—
9.0	Dent	Kernels fully dented; dry matter accumulation almost complete	2,450	105
10.0	Physiological maturity	Dry matter accumulation is complete; grain moisture is 35%	2,765	120

[a] Growing degree days based on a minimum temperature of 50°F and a maximum of 86°F; may be referred to as DD_{50} units.

Source: Adapted from *Illinois Agronomy Handbook*, *1991–1992,* University of Illinois, Urbana, IL.

2.2.4 Composition of Whole-Grain Field Corn

Component	%
Carbohydrate	72.2
Water	13.8
Protein	8.9
Fat	3.9
Ash	1.2

Component	Value
Digestible energy	3,610 kcal/kg
Protein	10.0%
Lysine	0.13%
Methionine + cystine	0.18%
Tryptophan	0.09%
Calcium	0.01%
Phosphorus	0.31%
Fiber	2.0%
Ether extract	3.9%

Component	%
Water	13.5
Protein	10.0
Oil	4.0
Starch	61.0
Sugars	1.4
Pentosans	6.0
Crude fiber	2.3
Ash	1.4
Potassium	0.40
Phosphorus	0.43
Magnesium	0.16
Sulfur	0.14
Other minerals	0.27
Other substances (organic acids, etc.)	0.4
Total	100.0

The germ contains about 35% oil, 20% protein, and 10% ash.

2.2.4.1 Composition of Whole Grain, Ground

Component	Value
Calories/100 g	355
Protein (%)	9.2
Fat (%)	3.9
Total calcium (mg/lb)	20
Total phosphorus (mg/lb)	256
Total potassium (mg/lb)	284
Carbohydrates (%)	73.7

2.2.5 Ethanol Production

In the U.S., nearly 500 million bu corn (about 7% of the crop) goes into ethanol production annually, adding about $3 billion annually to farm income. One bushel of corn will produce 2.5 gal ethanol.

In 2001, the ethanol industry's capacity exceeded 2 billion gal annually. The industry added 1 billion gal capacity in 2 years.

2.2.6 Corn Production Statistics

TABLE 2.11
U.S. Corn Acreage, Grain Yield, and Production, 1950–2000

Year	Planted Acres (millions)	Harvested Acres (millions)	Grain Production (million bu)	Grain Yield (bu/acre)
1950	82,900	72,400	2,764	38.2
1951	83,275	71,191	2,629	36.9
1952	82,230	71,353	2,981	41.8
1953	81,574	70,738	2,882	40.7
1954	82,185	68,668	2,708	39.4
1955	80,932	68,462	2,873	42.0
1956	77,828	64,877	3,075	47.4
1957	73,180	63,065	3,045	48.3
1958	73,351	63,549	3,356	52.8
1959	82,742	72,091	3,825	53.1
1960	81,425	71,422	3,907	54.7
1961	65,919	57,634	3,598	62.4
1962	65,017	55,726	3,606	64.7
1963	68,771	59,227	4,019	67.9
1964	65,823	55,367	3,484	62.9
1965	65,171	55,392	4,103	74.1
1966	66,347	57,002	4,168	73.1
1967	71,156	60,694	4,860	80.1
1968	65,126	55,980	4,450	79.5
1969	64,264	54,574	4,687	85.9
1970	66,863	57,358	4,152	72.4
1971	74,179	64,123	5,646	88.1
1972	67,513	57,513	5,580	97.0
1973	72,253	62,143	5,671	91.3
1974	77,935	65,405	4,701	71.9
1975	78,719	67,625	5,841	86.4
1976	84,588	71,506	6,289	88.0
1977	84,328	71,614	6,505	90.8
1978	81,675	71,930	7,268	101.0
1979	81,394	72,400	7,928	109.5
1980	84,043	72,961	6,639	91.0
1981	84,097	74,524	8,119	108.9
1982	81,857	72,719	8,235	113.2
1983	60,207	51,479	4,174	81.1
1984	80,517	71,897	7,672	106.7
1985	83,398	75,209	8,875	118.0
1986	76,580	68,907	8,226	119.4
1987	66,200	59,505	7,131	119.8
1988	67,717	58,250	4,929	84.6
1989	72,322	64,783	7,532	116.3
1990	74,166	66,952	7,934	118.5
1991	75,957	68,822	7,475	108.6

continued

TABLE 2.11 (CONTINUED)
U.S. Corn Acreage, Grain Yield, and Production, 1950–2000

Year	Planted Acres (millions)	Harvested Acres (millions)	Grain Production (million bu)	Grain Yield (bu/acre)
1992	79,311	72,077	9,477	131.5
1993	73,239	62,933	6,338	100.7
1994	78,921	72,514	10,051	138.6
1995	71,479	65,210	7,400	113.5
1996	79,229	72,644	9,233	127.1
1997	76,537	72,671	9,207	126.7
1998	80,187	72,604	9,761	134.4
1999	74,386	70,487	9,430	133.8
2000	74,545	72,732	9,968	137.1

Source: Department of Agricultural Economics, Kansas State University, Manhattan. With permission.

TABLE 2.12
U.S. Acreage, Yield, Production, and Value for Corn Grain and Silage, 1991–2000

Year	Area Planted (1,000 acres)	Area Harvested (1,000 acres)	Yield/Harvested Acre[a]	Production[b]	Marketing Year Average Price/bu ($)
		Corn Grain			
1991	75,957	66,822	108.7	7,474,765	2.37
1992	79,311	72,077	131.5	9,476,689	2.07
1993	73,239	62,933	100.7	6,337,730	2.50
1994	78,921	72,514	138.6	10,050,520	2.26
1995	71,479	55,210	113.5	7,400,051	3.24
1996	79,229	72,644	127.1	9,232,557	2.71
1997	79,537	72,671	126.7	9,206,632	2.43
1998	60,165	72,569	134.4	9,756,665	1.94
1999	77,366	70,467	133.6	9,430,612	1.62
2000[c]	74,545	72,732	137.1	9,968,356	1.85
		Corn for Silage			
1991	6,140	13.2	61,216		
1992	6,069	14.4	87,663		
1993	6,823	11.9	61,131		
1994	5,717	15.8	90,170		
1995	5,321	14.7	76,181		
1996	5.607	15.4	86,561		
1997	6,054	16.1	97,192		
1998	5,913	16.1	95,479		
1999	6,037	15.8	95,633		
2000[c]	5,866	16.8	96,536		

[a] Yield/harvested acre shown in bushels for corn grain and tons for corn for silage.
[b] Production shown in 1,000 bu for corn grain and 1,000 tons for corn for silage.
[c] Preliminary.

Source: National Agricultural Statistics Service, Crops Branch, Washington, D.C., 2001.

TABLE 2.13
Corn Planted in the U.S. (1,000 acres), 1998–2000

State	1998	1999	2000
Alabama	300	220	230
Arizona	50	50	56
Arkansas	235	105	180
California	600	525	540
Colorado	500	350	400
Connecticut	35	38	38
Delaware	169	169	165
Florida	160	90	85
Georgia	500	350	400
Idaho	145	165	195
Illinois	10,600	10,600	11,200
Indiana	5,800	5,600	5,700
Iowa	12,500	12,100	12,300
Kansas	3,000	3,150	3,450
Kentucky	1,300	1,320	1,330
Louisiana	700	340	360
Maine	34	33	28
Maryland	470	470	400
Massachusetts	25	26	25
Michigan	2,300	2,200	2,200
Minnesota	7,300	7,100	7,100
Mississippi	550	340	410
Missouri	2,650	2,650	2,650
Montana	60	65	60
Nebraska	8,800	8,600	8,500
Nevada	—	—	4
New Hampshire	15	15	15
New Jersey	120	110	90
New Mexico	140	150	150
New York	1,130	1,150	980
North Carolina	860	750	730
North Dakota	970	600	1,060
Ohio	3,550	3,450	3,550
Oklahoma	270	430	300
Oregon	55	45	55
Pennsylvania	1,550	1,500	1,550
Rhode Island	3	3	2
South Carolina	350	300	310
South Dakota	3,900	3,600	4,300
Tennessee	700	630	650
Texas	2,400	1,950	2,100
Utah	62	61	64
Vermont	112	106	90
Virginia	500	500	470
Washington	160	155	155
West Virginia	60	60	55
Wisconsin	3,700	3,600	3,500
Wyoming	95	65	95
U.S. Total	80,165	77,366	79,545

Source: Crops Branch, National Agricultural Statistics Service, Washington, D.C., 2001.

TABLE 2.14
U.S. Corn Yield and Production, 1998–2000

	Area Harvested (1,000 acres)			Yield/Harvested Acre (bu)			Production (1,000 bu)		
State	**1998**	**1999**	**2000[a]**	**1998**	**1999**	**2000[a]**	**1998**	**1999**	**2000[a]**
Alabama	200	200	165	63.0	103.0	65.0	12,600	20,600	10,725
Arizona	30	30	33	175.0	195.0	196.0	5,250	5,650	6,466
Arkansas	215	100	175	100.0	130.0	130.0	21,500	13,000	22,750
California	245	165	235	160.0	170.0	170.0	39,200	31,450	39,950
Colorado	1,070	1,120	1,160	145.0	142.0	127.0	155,150	159,040	149,660
Delaware	155	154	156	100.0	69.0	162.0	15,500	13,706	25,272
Florida	55	40	28	62.0	93.0	75.0	3,410	3,720	2,100
Georgia	265	300	300	65.0	103.0	107.0	22,525	30,900	32,100
Idaho	52	55	57	150.0	155.0	160.0	7,600	8,525	9,120
Illinois	10,450	10,650	11,050	141.0	140.0	151.0	1,473,450	1,491.000	1,666,550
Indiana	5,550	5,670	5,550	137.0	132.0	147.0	760,350	746,440	615,650
Iowa	12,200	11,600	12,000	145.0	149.0	145.0	1,769,000	1,756,200	1,740,000
Kansas	2,650	2,960	3,200	147.0	141.0	130.0	416,950	420,160	416,000
Kentucky	1,160	1,160	1,230	115.0	105.0	130.0	135,700	123,900	159,900
Louisiana	540	330	370	61.0	121.0	116.0	43,740	39,930	42,920
Maryland	400	360	405	109.0	93.0	155.0	43,600	33,480	62,775
Michigan	2,050	1,950	1,970	111.0	130.0	124.3	227,550	253,500	244,280
Minnesota	6,750	6,600	6,600	153.0	150.0	145.0	1,032,750	990,000	957,000

Mississippi	500	310	365	66.0	117.0	100.0	43,000	36,270	36,500
Missouri	2,500	2,550	2,770	114.0	97.0	143.0	265,000	247,350	396,110
Montana	16	16	16	115.0	110.0	140.0	2,070	1,960	2,520
Nebraska	6,550	6,300	6,050	145.0	139.0	126.0	1,239,750	1,153,700	1,014,300
New Jersey	98	60	75	92.0	37.0	134.0	9,106	2,220	10,050
New Mexico	65	63	73	165.0	160.0	160.0	14,025	14,940	11,660
New York	560	590	460	114.0	101.0	96.0	66,120	59,590	47,040
North Carolina	770	640	650	70.0	60.0	116.0	53,900	51,200	75,400
North Dakota	625	655	930	107.0	117.0	112.0	66,275	76,635	104,160
Ohio	3,340	3,200	3,300	141.0	126.0	147.0	470,940	403,200	465,100
Oklahoma	220	260	270	130.0	145.0	140.0	26,600	40,600	37,600
Oregon	33	30	29	190.0	175.0	180.0	6,270	5,250	5,220
Pennsylvania	1,050	660	1,060	111.0	70.0	127.0	116,550	61,600	137,160
South Carolina	275	275	280	40.0	70.0	65.0	11,000	19,250	18,200
South Dakota	3,550	3,250	3,650	121.0	113.0	112.0	429,550	367,250	431,200
Tennessee	620	570	590	96.0	102.0	114.0	59,520	56,140	67,260
Texas	1,650	1,770	1,900	100.0	129.0	124.0	165,000	226,330	235,600
Utah	24	20	21	141.0	143.0	144.0	3,364	2,660	3,024
Virginia	300	280	330	84.0	78.0	146.0	25,200	21,840	48,180
Washington	100	100	100	190.0	160.0	165.0	19,000	16,000	18,500
West Virginia	34	20	35	60.0	65.0	130.0	2,720	1,300	4,550
Wisconsin	2,950	2,850	2,750	137.0	143.0	132.0	404,150	407,550	363,000
Wyoming	60	52	62	127.0	116.0	132.0	7,620	6,136	6,164
U.S. Total	72,569	70,467	72,732	134.4	133.6	137.1	9,756,665	9,430,612	9,968,356

[a] Preliminary

Source: Crops Branch, National Agricultural Statistics Service, Washington, D.C., 2001.

TABLE 2.15
U.S. Total and Per Capita Civilian Consumption of Corn and Corn Products as Food, 1990–1999

Calendar year[a]	Total Consumed (million bu)[b]	Per Capita Consumption of Food Products				
		Flour and Meal (lb)	Hominy and Grits (lb)	Syrup (lb)	Sugar (lb)	Starch (lb)
1990	736	14.4	2.9	67.3	3.8	4.0
1991	763	14.9	2.8	72.0	3.9	4.0
1992	791	15.4	2.6	72.9	3.9	4.2
1993	834	15.8	3.1	76.2	3.9	4.4
1994	868	16.1	3.6	78.4	3.9	4.6
1995	895	16.4	4.1	80.2	4.0	4.8
1996	939	18.8	4.6	82.0	4.0	5.0
1997	968	17.1	5.0	85.9	3.8	4.9
1998	976	17.4	5.5	87.3	3.7	4.8
1999[c]	990	17.7	5.9	88.0	3.6	4.8

[a] Data shown for marketing year, September 1 to August 31.
[b] Includes allowance for quantities used as hominy and grits.
[c] Preliminary.

Source: Economics Research Service, Washington, D.C., 2001. With permission. All figures are estimates based on data from private industry sources, the U.S. Department of Commerce, the Internal Revenue Service, and other government agencies.

TABLE 2.16
World Corn Production by Country shown as Percent of Total, 2000

Country	%
India	2
Argentina	3
Brazil	6
European Union	7
China	10
U.S.	43
Others	18

Source: Foreign Agriculture Service, Washington, D.C., 2001.

TABLE 2.17
World Corn Consumption by Country, 2000

Country	Million Bu
Romania	214.6
Canada	350.3
Egypt	405.5
India	472.4
Japan	631.9
Mexico	956.6
Brazil	1,393.6
European Union	1,606.5
China	4,724.1
U.S.	7,739.9
Others	5,300.8
Total	23,796.3

Source: Foreign Agriculture Service, Washington, D.C., 2001.

TABLE 2.18
World Corn Exports by Country Shown as Percent of Total, 2000

Country	%
Ukraine	1
South Africa	2
China	6
Argentina	14
U.S.	75
Others	2

Source: Foreign Agriculture Service, Washington, D.C., 2001.

TABLE 2.19
Annual Percent Change in World Corn Yields, 1950–1995 (3-year average)

Year	% Change
1950–1960	2.6
1960–1970	2.4
1970–1980	2.7
1980–1990	1.3
1990–1995	1.7

Source: Foreign Agriculture Service, Washington, D.C., unpublished printout, 1996; updated 1997.

TABLE 2.20
U.S. Corn Acreage, Yield, and Production for Grain and Silage, 1991–2000

	Corn for Grain			Corn for Silage		
Year	Area Harvested (1,000 acres)	Yield (bu/acre)	Production (1,000 tons)	Area Harvested (1,000 acres)	Yield (bu/acre)	Production (1,000 tons)
1991	68,822	108.6	7,474765	6,140	13.2	81,216
1992	72,077	131.5	9,476,698	6,069	14.4	87,663
1993	62,933	100.7	6,337,730	6,823	11.9	81,131
1994	72,514	138.6	10,050,520	5,717	15.8	90,170
1995	65,210	113.5	7,400,051	5,321	14.7	78,181
1996	72,644	127.1	9,232,557	5,607	15.4	86,581
1997	72,671	126.7	9,206,632	6,054	16.1	97,192
1998	72,589	134.4	9,756,685	5,913	16.1	95,479
1999	70,487	133.6	9,430,612	6,037	15.8	95,633
2000[a]	72,732	137.1	9,968,358	5,868	16.8	98,538

[a] Preliminary.

Source: Crops Branch, National Agricultural Statistics Service, Washington, D.C., 2001.

TABLE 2.21
Corn Grain Acreage, Yield, and Production by Continent and Country, 1999–2000

Location	Area Harvested (10,000 ha)	Grain Yield (metric tons/ha)	Production (1,000 metric tons)
		Continent	
North America	37,375	7.18	267,645
Central America	1,863	1.49	2,775
South America	18,050	2.99	53,995
European Union	4,145	8.92	36,762
Eastern Europe	7,028	4.39	30,840
USSR	2,155	2.30	4,946
Africa	23,959	1.67	40,042
Asia	43,971	3.71	163,289
Middle East	1,012	3.47	3,507
Oceania	76	6.71	510
World total	140,119	4.32	605,147
		Country	
U.S.	28,528	8.40	239,549
China	25,704	4.94	128,086
Brazil	12,500	2.53	31,600
Mexico	7,900	2.47	17,000
India	6,510	1.76	11,470
South Africa	3,868	2.74	10,584

Source: Foreign Agriculture Service, Washington, D.C., 2001.

TABLE 2.22
Corn: Percent of Areas Receiving Fertilizer Applications, All States Surveyed, 1995–1999[a]

Year	Nitrogen (%)	Phosphate (%)	Potash (%)
1995	97	81	70
1996	98	85	73
1997	99	84	72
1998	98	63	66
1999	98	82	67

[a] All values shown as percents and based on number of acres receiving one or more applications of a specific fertilizer ingredient.

Source: Environmental, Economics and Demographics Branch, National Agriculture Statistics Service, Washington, D.C., 2001.

2.2.7 Corn Plant Nutrition

TABLE 2.23
Nutrient Elements Contained in the Stovers, Grains, and Roots of a 150-Bu Corn Crop

Compound or Element	Approximate (lb/acre)	Supplied by or Approximate Equivalent
Water	6,500,000 to 8,250,000	29 to 36 inches of rain
Oxygen	10,200	Air is about 20% oxygen
Carbon	7,800 carbon or 28,500 CO_2	Carbon contained in 6 tons of coal
Nitrogen	310	Nitrogen, phosphorus, and potassium are the three nutrient elements contained in most mixed fertilizers
Phosphorus (P × 2.29 = phosphate)	120 lb as phosphate or 52 lb as P	Approx. equivalent is 1,200 lb of 25-10-20 fertilizer
Potassium (K x 120 = potash)	245 lb as potash or 205 lb K	
Calcium	58	Approx. 150 lb agricultural limestone or equivalent
Sulfur	33	33 lb sulfur or equivalent
Magnesium	50	Approx. 215 lb epsom salt or 550 lb sulfate of potash-magnesia
Iron	3	15 lb iron sulfate or equivalent
Manganese	0.45	Approx. 1.3 lb manganese sulfate or equivalent
Boron	0.10	Approx. 1.0 lb borax or equivalent
Zinc	Trace	Small amount of zinc sulfate or equivalent
Copper	Trace	Small amount of copper sulfate or oxide
Molybdenum	Trace	Very small amount of sodium or ammonium molybdate

Note: Corn roots contain 75 lb N, 30 lb P_2O_5, 60 lb K_2O, and 9 lb S.

TABLE 2.24
Nutrient Elements Required to Produce 150 bu (8400 lb at 56 lb/bu) of Corn

Element	Grain		Stover		Total	
	(lb/acre)	(lb/bu)	(lb/acre)	(lb/bu)	(lb/acre)	(lb/bu)
Nitrogen	115	0.77	55	0.37	170	1.13
Phosphorus as phosphate	28	0.19	7	0.05	35	0.55
Potassium as potash	35	0.23	140	0.93	175	1.40
Calcium	1.3	0.01	35	0.23	36	0.24
Magnesium	10	0.07	29	0.19	39	0.26
Sulfur	11	0.07	8	0.05	19	0.13
Chlorine	4	0.03	68	0.45	72	0.48
Iron	0.1	—[a]	1.8	0.01	1.9	0.01
Manganese	0.05	—	0.25	—	0.30	—
Copper	0.02	—	0.08	—	0.10	—
Zinc	0.17	—	0.17	—	0.34	—
Boron	0.04	—	0.12	—	0.16	—
Molybdenum (mo)	0.005	—	0.003	—	0.008	—

[a] Less than 0.0005.

Source: *Changing Patterns in Fertilizer Use*, 1968, Soil Society of America, Madison, WI. With permission.

TABLE 2.25
Corn Crop Nutrient Element Utilization (lb/acre)

Yield	Nitrogen	Phosphorus	Potassium	Magnesium	Sulfur
100 bu/acre	150	60	125	30	18
150 bu/acre	220	80	195	40	25
180 bu/acre	240	100	240	50	30
200 bu/acre	266	114	266	65	33

TABLE 2.26
Uptake of Major Elements and Micronutrients by a 10-Ton/Acre Corn Crop

Major Elements	kg
Nitrogen	240
Phosphorus as phosphate	102
Potassium as potash	120
Calcium	43
Magnesium	58
Sulfur	30
Micronutrients	**mg**
Boron	36
Copper	20
Iron	120
Manganese	36
Zinc	60

Source: International Soil Fertility Manual, 1995, Potash & Phosphate Institute, Norcross, GA.

TABLE 2.27
Major Element and Micronutrient Removal by Corn Grain and Stover at Two Grain Yields

Element	Yield			
	9.5 tons/ha		6.3 tons/ha	
	Grain	Stover	Grain	Stover
	kg/ha			
Nitrogen	129	62	100	63
Phosphorus as phosphate	71	18	40	23
Potassium as potash	47	188	29	92
Calcium as oxide	2.1	55	1.5	15
Magnesium as oxide	18	55	9.3	28
Sulfur	12	9	7.8	9
	g/ha			
Boron	50	140	—	—
Copper	20	90	40	30
Iron	110	2020	—	—
Manganese	60	280	70	940
Zinc	190	190	110	200

Source: *International Fertilizer Association World Fertilizer Use Manual,* 2000, Paris.

TABLE 2.28
Major Requirements of Corn during Growing Season (Yield = 11.8 tons/ha)

Plant Age (days)	Major Amount Absorbed (kg/ha/day)		
	N	P_2O_5	K_2O
20–30	1.7	0.39	1.7
30–40	6.7	1.55	9.95
40–50	8.3	2.32	11.56
50–60	5.3	2.06	4.42

Source: *International Fertilizer Association World Fertilizer Use Manual,* 2000, Paris.

TABLE 2.29
Increase Elemental Content of Corn Plants Produced by Nitrogen Fertilization

Element	No Fertilizer	180 N kg/ha
Nitrogen, %	2.36	3.02
Phosphorus, %	0.18	0.26
Potassium, %	2.22	2.44
Calcium, %	0.66	0.68
Magnesium, %	0.24	0.26
Boron, ppm	12	18
Copper, ppm	10	14
Iron, ppm	163	162
Manganese, ppm	40	47
Zinc, ppm	22	36
Yield, tons/ha	7.4	8.7

Source: *International Soil Fertility Manual*, Potash & Phosphate Institute, Norcross, GA.

TABLE 2.30
Plant Nutrient Elements Absorbed by 180-Bu/Acre Corn Crop during Successive 25-day Growing Periods (%)

Nutrient	First (Early)	Second (Growth)	Third (Silk)	Fourth (Grain)	Fifth (Mature)
Nitrogen	8	35	31	20	6
Phosphate	4	27	36	25	8
Potash	9	44	31	14	2

Source: Efficienct Fertilizer Use Manual — Soil Fertility, IMC Global, Inc., Lake Forest, IL., 2001.

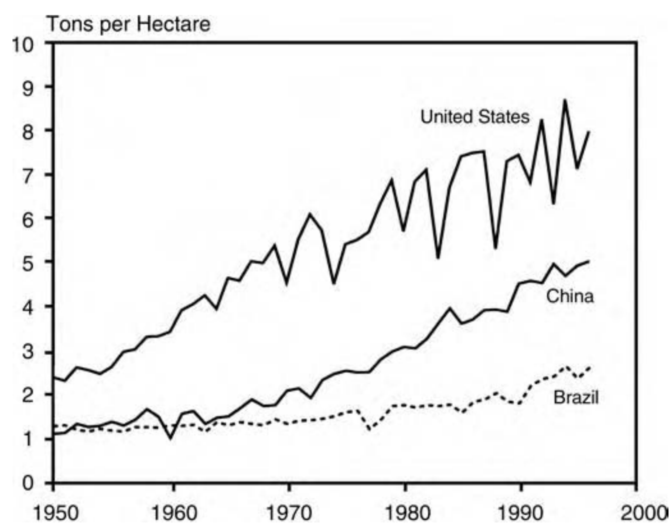


FIGURE 2.1 Corn yields in the U.S., China, and Brazil, 1950–1996. (*Source*: *The Agricultural Link*, 1997, Worldwatch Paper 136, Worldwatch Institute.)

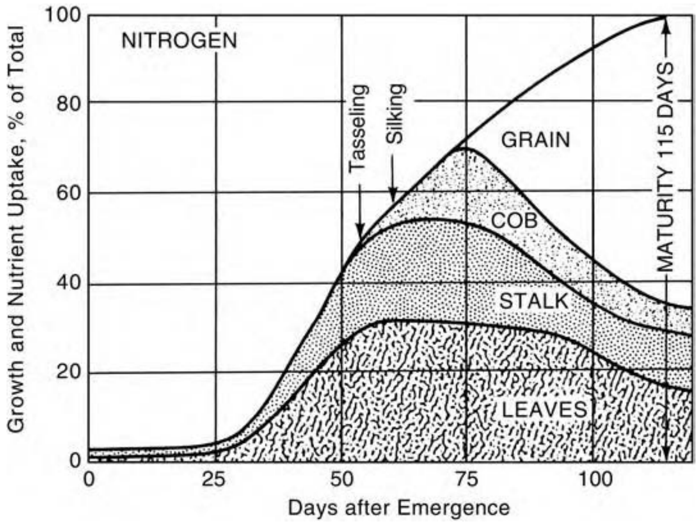


FIGURE 2.2 Nitrogen uptake and distribution in corn.

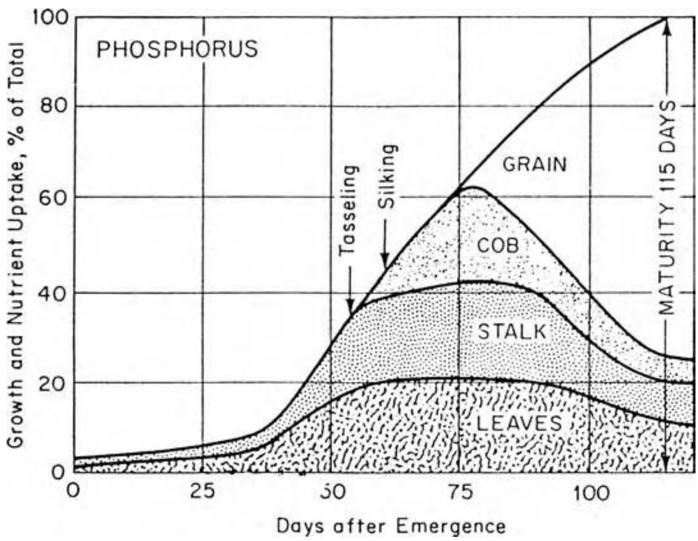


FIGURE 2.3 Phosphorus uptake and distribution in corn.

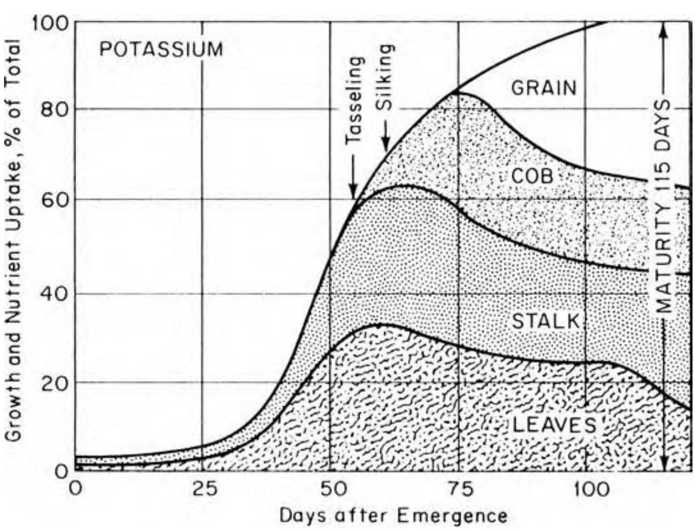


FIGURE 2.4 Potassium uptake and distribution in corn.

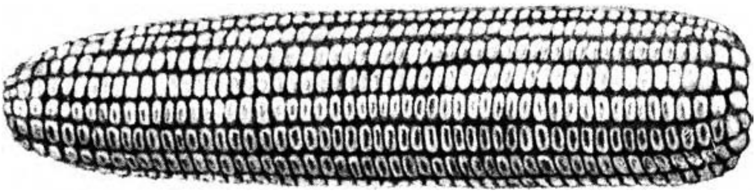


FIGURE 2.5 Normal ears on well fertilized, high-producing corn often weigh 5 oz to 8 oz.

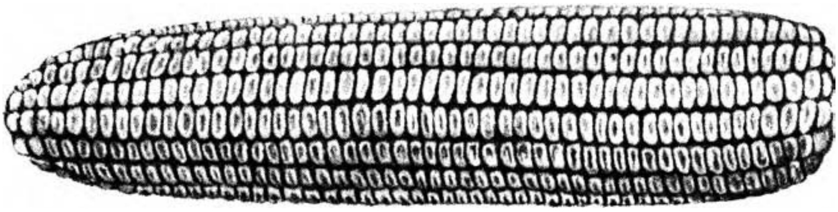


FIGURE 2.6 Big ears (in excess of 8 oz), with kernels covering the tips of the cobs.

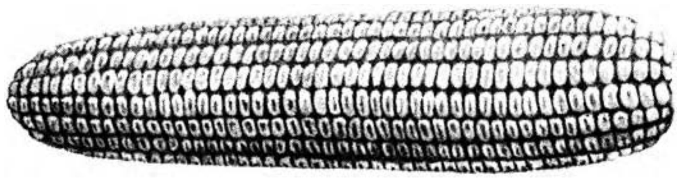


FIGURE 2.7 Small ears may be signs of low fertility.

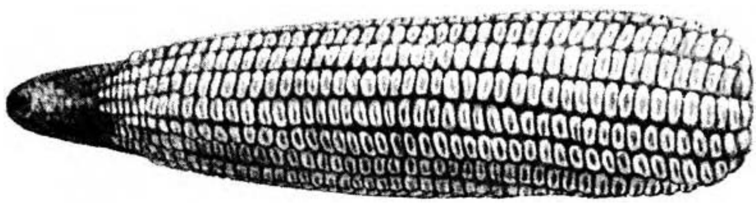


FIGURE 2.8 Poorly filled tips and loose, chaffy kernels may indicate potassium deficiency.

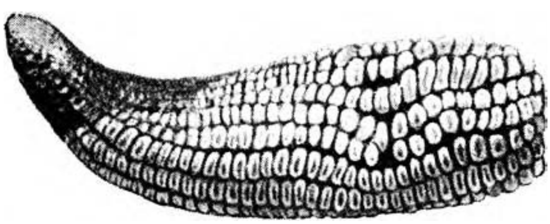


FIGURE 2.9 Phosphorus deficiency results in small, twisted ears and underdeveloped kernels from lack of pollination.

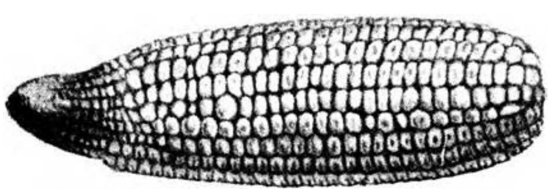


FIGURE 2.10 Nitrogen deficiency at critical times results in small ears; kernels at the tips do not fill.



FIGURE 2.11 Dry weather slows silking; kernels are not well pollinated.

2.2.8 Nutrient Element Deficiencies[1]

2.2.8.1 Boron (B)

2.2.8.1.1 Deficiency Symptoms

Boron-deficient plants are stunted; they have short, stout stems that appear oval in cross-section. Leaves are pale green, short, and more erect than normal. Boron deficiency reduces the numbers and sizes of ears and also affects pollination by preventing the growth of the pollen tube. As a result, barren ears are commonly produced by B-deficient plants and grain yields are severely reduced.

Yellow interveinal lesions on younger leaves: Because B is not readily transferred from old to young leaves, symptoms of deficiency appear first and are more severe on young leaves. Old leaves usually remain green and appear healthy. The youngest leaves are affected before unrolling fully from the sheaths of previous leaves. Affected leaves are short and held erect. They are pale green, with short, yellow interveinal lesions throughout their laminae. The chlorotic lesions produce no definite patterns.

2.2.8.1.2 Problem Soils

Boron deficiency is likely to occur in:

- Soils derived from parent material low in B such as acid igneous rocks or fresh water sediments
- Sandy soils from which boron has been leached
- Alkaline soils, especially those containing free lime
- Soils low in organic matter
- Acid peat and muck soils

2.2.8.1.3 Correcting Deficiency

Boron deficiency can be corrected by soil applications or foliar sprays of boron fertilizers. Soil applications are more effective if broadcast and mixed into the soil some months before sowing. Borax, boric acid, and chelated B compounds are suitable soil applications but only boric acid or chelated B compounds are suitable as foliar sprays. Foliar sprays should be applied about 5 to 6 weeks after seedling emergence or as soon as symptoms appear. While soil applications often remain effective for many years, foliar sprays have little residual value and must be applied to every crop.

Soil tests can be used to estimate the amount of available B in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

2.2.8.2 Calcium (Ca)

2.2.8.2.1 Deficiency Symptoms

Calcium deficiency produces very stunted plants. Stems very short and stout; the foliage is green, often distorted, and appears torn and ragged. If the deficiency persists, young leaves have difficulty emerging fully and unrolling, and shoots may die before reaching maturity. Calcium deficiency

reduces grain yields. Mildly affected crops develop small ears and distorted tassels. If the deficiency is severe, no ears or tassels may develop and plants may die before maturity.

Torn or malformed young leaves: Because Ca is not readily transferred from old to young tissues, symptoms appear first and are more severe on young leaves. If the deficiency persists, young leaves become very short and are held erect. Symptoms begin with young leaves that turn pale green and develop yellow to white interveinal lesions. The chlorotic areas grow and the laminae tear easily at those points. When new leaves develop, they often have holes in the laminae. The torn, malformed leaves give the plants a ragged appearance. When the deficiency is very severe, the youngest leaves do not fully unroll. They remain joined at their tips and produce a ladder-like appearance. In extreme cases, the youngest leaves die before emerging. Old leaves remain green and appear healthy.

Fan-shaped stems: Calcium deficiency produces short, stout stems that appear flattened in cross-section. The sheaths of old leaves often pull away from the stems, producing a fan-shaped appearance after the leaves crowd together at the tops.

2.2.8.2.2 Problem Soils

Calcium deficiency is likely to occur in:

- Acid sandy soils where Ca is leached by heavy rainfall
- Strongly acid peat and muck soils in which total Ca is low
- Alkaline or sodic soils in which high exchangeable sodium (Na) and pH depress the uptake of Ca
- Soils with high levels of soluble aluminum (Al) and low levels of exchangeable Ca

2.2.8.2.3 Correcting Deficiency

Calcium deficiency can be corrected by broadcasting a suitable fertilizer onto the soil and mixing it in some months before sowing. Where the chief problem is simply a lack of Ca, suitable fertilizers are gypsum (calcium sulfate) and calcium nitrate or chloride. However, if the pH is low, lime or limestone (calcium carbonate) and dolomite (a mixture of calcium and magnesium carbonates) are more suitable.

A soil test can be used to determine the lime or Ca requirement. However, since the correct rate of application depends on soil type and the crop to be grown, advice should be sought on fertilizer practices used on similar soils in the region. The excessive use of lime may induce deficiencies of K, Mg, Fe, Mn, Zn, or Cu; and care should be taken to prevent over-liming.

2.2.8.3 Copper (Cu)

2.2.8.3.1 Deficiency Symptoms

Copper-deficient corn plants appear patchy. In copper-poor areas, plants are stunted; they have thin, spindly stems and pale green foliage. Affected plants often appear limp and wilted. Copper-deficient plants produce small ears that set few grains because Cu deficiency interferes with the production of fertile pollen. If a deficiency is very severe, many plants die before reaching maturity.

Weather-tipped young leaves: Because Cu is not readily transferred from old to young leaves, symptoms appear first and are more severe on young leaves. Old leaves usually remain green and appear healthy. Young leaves become limp and turn pale green. Pale yellow to white, interveinal and marginal chlorosis then develops at the leaf tips. If the deficiency persists, the affected tissue dies, turns pale brown, and twists or rolls into a tube, giving the leaves a weather-tipped appearance.

Deaths of shoots: When the deficiency persists and becomes very severe, the youngest leaves often die before emerging from the sheaths of older leaves. The affected plants seldom mature. Tillers may develop but they die before maturity.

2.2.8.3.2 Problem Soils

Copper deficiency is likely to occur in:

- Peat and muck soils in which organic matter ties up soluble Cu in forms less available to plants
- Alkaline sands in which total Cu is low
- Leached acid soils in which total Cu is low
- Soils formed from rocks low in Cu

2.2.8.3.3 Correcting Deficiency

Foliar sprays and soil applications of Cu salts such as copper sulfate (bluestone) or copper chelates have corrected Cu deficiencies. Soil applications should be mixed into the soil some weeks before sowing. However, soil applications may fail to correct the deficiencies in some seasons and symptoms may reappear in the crop. If this occurs, foliar sprays should be applied immediately.

A reliable remedy is to apply foliar sprays of 0.5 to 1% solutions of soluble Cu salts (for example, 0.5 to 1 kg copper sulfate per 100 L water per ha); the first application should occur 4 to 6 weeks after seedling emergence. Additional sprays should be applied as soon as symptoms reappear.

Tests can be used to estimate the amount of available Cu in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

2.2.8.4 Iron (Fe)

2.2.8.4.1 Deficiency Symptoms

Iron-deficient plants are stunted and have pale green to yellow leaves. Stems are thin and spindly and usually green, although faint red-purple stripes may appear on the lower stems and older leaf sheaths when the deficiency is severe. Affected plants develop small ears that set fewer grains than normal. Kernel size may be reduced also if the deficiency is severe. As a result, grain yields may be severely reduced.

Interveinal chlorosis on younger leaves: Because Fe is not readily transferred from old to young leaves, symptoms develop first and are more severe on young leaves. Symptoms begin when young leaves turn pale green. Pale yellow chlorosis then develops throughout the interveinal tissues of whole leaves. The veins become green and prominent. When the deficiency persists or becomes severe, the interveinal tissue turns dark yellow and the veins become pale green. At this stage, interveinal yellowing is often seen also on the youngest, unrolled leaves.

2.2.8.4.2 Problem Soils

Iron deficiency is likely to occur in:

- Calcareous soils in which levels of soluble Fe are low
- Waterlogged soils
- Acid soils that have excessively high levels of soluble Mn, Zn, Cu, or Ni that depress plant uptake of Fe
- Sandy soils low in total Fe
- Peat and muck soils in which organic matter ties up Fe

2.2.8.4.3 Correcting Deficiency

While soil applications of inorganic Fe salts such as iron sulfates or chlorides have corrected the deficiencies in some soils, the applied Fe quickly becomes insoluble and less available to plants. Iron salts of various organic chelates show promise as soil applications because the chelates have

the ability to keep Fe in solution. For acid soils, FeEDTA is the most effective chelate. FeHEDTA and FeDTPA are best on neutral soils and FeEDDHA works on alkaline soils. However, to be effective, large amounts of chelates may be required and may prove too costly.

Another effective remedy is to apply solutions of inorganic salts or chelates to the foliage (1% solutions or 1 kg salt per 100 L water per ha). Because Fe is so immobile in plants, sprays must be applied every 10 to 15 days to provide Fe to new leaves. Advice on fertilizer practices used on similar soils in the region should be sought to obtain the best remedies for local conditions.

2.2.8.5 Magnesium (Mg)

2.2.8.5.1 Deficiency Symptoms

Magnesium-deficient corn plants are stunted. They have thin, spindly stems, pale green to yellow foliage, and rust-brown lesions. Magnesium-deficient crops develop small ears and kernel size may also be reduced, causing low grain yields.

Interveinal chlorosis on older leaves: Because Mg is readily transferred from old to young leaves, symptoms appear first and are more severe on old leaves. Symptoms work their way up the plants to younger leaves if the deficiency persists. Old leaves turn pale green. Pale yellow, interveinal chlorosis develops in the mid-sections of the leaves and advances toward the bases and the tips. The chlorotic tissue dies and leaves intermittent, pale brown, necrotic lesions between the veins. The youngest leaves usually remain green and appear healthy.

Rust-brown striped leaves: As a deficiency becomes more severe, rust-brown stripes appear on the margins and in adjacent interveinal areas on old leaves. Eventually, the brown striping extends completely over leaves and combines with the brown necrotic lesions developed in interveinal areas. Soon afterward, the margins and tips die and turn dark brown. In severe cases, the lower leaves die and hang down around the stems.

2.2.8.5.2 Problem Soils

Magnesium deficiency is likely to occur in:

- Acid sandy soils from which Mg has been leached
- Strongly acid peat and muck soils in which total Mg is low
- Soils over-fertilized with Ca (for example, lime) or K, thus inhibiting uptake of Mg

2.2.8.5.3 Correcting Deficiency

Magnesium deficiency on acid soils is best corrected by broadcasting dolomite (a mixture of calcium and magnesium carbonates) and mixing it into the soil some months before sowing. When the problem is strictly a deficiency of Mg, hand applications of magnesium sulfate or chloride can be made at or before planting. Tests can be used to estimate the amount of soluble and exchangeable Mg in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

Magnesium deficiency in existing crops can be corrected by applying soluble salts such as magnesium sulfate, chloride, or nitrate with irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number needed to supply the requirements of the crop.

2.2.8.6 Manganese (Mn)

2.2.8.6.1 Deficiency Symptoms

Crops suffering from Mn deficiency often appear patchy. Within Mn-poor areas, plants are stunted; they have thin, short stems and pale green to yellow foliage. Mild deficiencies of Mn do not appear to affect grain yields greatly. However, if the deficiency persists and becomes severe, the numbers and sizes of ears and kernels are reduced, thereby reducing grain yields.

Interveinal chlorosis on older leaves: Manganese is partly mobile in corn, and some of the element is transferred from old to young leaves when a deficiency occurs. As a result, symptoms appear first on middle leaves and spread mainly to older leaves. Younger leaves are also affected if the deficiency persists and becomes severe. Middle leaves turn pale green and develop a pale yellow interveinal chlorosis that extends the full lengths of the leaves. The veins remain pale green and are easily recognizable. As the deficiency becomes more severe, this symptom develops on old leaves. It rarely appears on the youngest leaves, which remain pale green.

White interveinal flecks: When the deficiency is severe, crystalline, white flecks appear within the interveinal chloroses. Eventually, all chlorotic tissue dies and turns white, leaving the veins green and very prominent. Necrosis develops near the margins and tips of old leaves and extends toward the bases until whole leaves die and turn pale brown.

Wavy leaf margins: Affected leaves often appear limp or wilted. Leaf margins curl down and appear excessively wavy.

2.2.8.6.2 Problem Soils

Manganese deficiency is likely to occur in:

- Strongly alkaline soils in which Mn is less available to plants
- Poorly drained, peaty soils in which Mn occurs in forms less available to plants
- Strongly acid, sandy soils from which soluble Mn has been leached
- Soils formed from rocks low in Mn

2.2.8.6.3 Correcting Deficiency

Foliar sprays and soil applications of Mn salts and oxides have been used to correct Mn deficiency. Soil applications are more effective when broadcast and mixed into the soil some weeks before sowing. However, foliar applications have generally been more successful than soil applications. One or more foliar sprays of 0.5 to 1% solutions of soluble Mn salts (for example, 0.5 to 1 kg manganese sulfate per 100 L water per ha) usually correct the deficiency. The first should be applied 5 to 6 weeks after seedling emergence. If the symptoms reappear, the spray should be repeated immediately. While soil applications usually last 5 to 6 years before fresh applications are needed, foliar sprays must be applied to every crop.

Soil tests can be used to estimate the amounts of available Mn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

2.2.8.7 Nitrogen (N)

2.2.8.7.1 Deficiency Symptoms

Corn is very sensitive to N supply and even mild deficiencies severely reduce growth. Nitrogen-deficient young plants are stunted and have thin, spindly stems and pale green to yellow, short, erect leaves. If the deficiency persists or occurs in more mature crops, the old leaves become pale yellow while young leaves remain green. Nitrogen-deficient plants usually produce single small ears. The small ears and the depression of kernel size severely reduce grain yields. Furthermore, the grain will be low in protein because N plays a central role in the formation of proteins.

Pale yellow older leaves: Because N is readily transferred from old to young leaves, symptoms appear first and are more severe on old leaves. Symptoms work their way up the plants to young leaves if the deficiency persists. Old leaves turn pale green. Pale yellow chlorosis then develops at the tips and advances down the leaves, usually along the mid-veins, producing V-shaped patterns. The chlorosis is followed by pale brown necrosis until entire leaves are affected and die, often hanging down around the lower stems.

Red stems: Some varieties develop red colors on the lower stems. This coloration is usually more intense on the sides facing the sun and is not present on the areas shaded by the leaf sheaths.

2.2.8.7.2 Problem Soils

Nitrogen deficiency is likely to occur in:

- Sandy soils leached by heavy rainfall or excessive irrigation
- Soils low in organic matter
- Soils with a long history of cropping and depleted of N supplies

However, even fertile soils may suffer temporary N deficiency when double-cropped, heavily leached, or waterlogged.

2.2.8.7.3 Correcting Deficiency

Nitrogen deficiency is corrected by increasing the level of available N in the soil by fallowing, which allows organic N to be converted to mineral N; by growing cover or cash crops of legumes, which can fix atmospheric N_2; or by adding nitrogenous fertilizers. Suitable fertilizers are urea, gaseous ammonia or ammonium sulfate, nitrates, or phosphates. Crop growth depends on the amount of N already in the soil.

A test can measure the amount of total N or nitrate (NO_3)-N in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

Nitrogen deficiency in existing crops can be corrected by applying soluble salts such as urea with irrigation water or as a foliar spray. Spray applications usually result in a rapid response of short duration, and additional sprays 10 to 14 days apart may be needed to supply enough N to the crop.

2.2.8.8 Phosphorus (P)

2.2.8.8.1 Deficiency Symptoms

Mild deficiencies cause reduced growth but few clearly recognizable leaf symptoms. When the deficiency is severe, plants are stunted and have short, stout stems and dark green, short, erect leaves. Some varieties may develop purple or red areas on leaves and stems. A deficient plant may produce only one small ear containing fewer, smaller kernels than usual. Grain yield is often severely reduced.

Purple older leaves: Because P is readily transferred from old to young leaves, symptoms appear first and are more severe on old leaves. They work their way up the plants to young leaves if the deficiency persists. In many varieties, purple or purple-red areas develop on the old dark green leaves. In some varieties, the purple is restricted to the mid-sections of leaves and may develop interveinal patterns. In other varieties, entire leaves are suffused with purple. Young leaves usually remain unaffected.

Dark yellow leaf tips: Yellow chlorosis develops at the tips of old leaves and advances toward the bases, usually in a broad front but sometimes along the margins. The chlorosis turns dark brown as the tissue dies.

Purple stems: Many varieties develop red or purple areas on the lower stems and old leaf sheaths. The colors are more intense on areas exposed to sunlight; stems are green beneath protecting leaf sheaths.

2.2.8.8.2 Problem Soils

Phosphorus deficiency is likely to occur in:

- Soils low in organic matter
- Soils in which cropping has depleted P supplies

- Highly weathered, Fe-rich acid soils in which phosphate is fixed in less available forms
- Soils whose topsoil has been lost during erosion
- Calcareous soils that contain P in forms that are less available to plants

2.2.8.8.3 Correcting Deficiency

Phosphorus deficiency can be corrected by applying phosphatic fertilizers at or before sowing. Suitable fertilizers are single or triple superphosphates or ammonium phosphates. The growth of crops depends on the amount of water-soluble phosphates and the rate of exchange between insoluble and soluble forms of P in the soil.

A test can be used to estimate the amount of available phosphate in a soil and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

Phosphorus deficiency in existing crops can be corrected by applying soluble salts such as ammonium phosphates with irrigation water. Spray applications of similar salts are usually not recommended because of the large number of applications needed to supply the requirements of the crop.

2.2.8.9 Potassium (K)

2.2.8.9.1 Deficiency Symptoms

Mild deficiencies of K cause stunted growth; plants have short, thin stems and pale green foliage. In severe deficiencies, plants become very stunted with short, spindly stems, pale green young leaves, and dead old leaves that hang down around the lower stems. Potassium deficiency severely reduces grain yield. An affected plant may produce a single small ear that is often very pointed and underdeveloped at the tip. Kernel size is smaller than normal.

Marginal necrosis on older leaves: Because K is readily transferred from old to young leaves, symptoms develop first and are more severe on old leaves. They work their way up the plants to younger leaves if the deficiency persists. Symptoms begin as a pale yellow chlorosis on the tips of old leaves. The chlorosis is followed rapidly by pale brown necrosis and both symptoms advance down the margins toward the bases, usually leaving the mid-veins and surrounding tissues pale green. Young leaves usually remain green and appear healthy.

Red stems: When the deficiency is mild, stems are usually pale green, but prominent red stripes develop on the lower stems and leaf sheaths if the deficiency persists or becomes severe.

2.2.9.9.2 Problem Soils

Potassium deficiency is likely to occur in:

- Soils low in organic matter
- Sandy soils formed from parent material low in K
- Light textured soils leached of K by heavy rainfall

2.2.8.9.2 Correcting Deficiency

Potassium deficiency is corrected by applying potassium nitrate, sulfate, or chloride to the soil at or before sowing. Crop yield depends on the amounts of water-soluble and exchangeable K in the soil. A test can measure the amount of available K in the soil and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

Potassium deficiency in existing crops can be corrected by applying soluble salts such as potassium sulfate, chloride, or nitrate with irrigation water. Foliar sprays of similar salts are not recommended because of the large number needed to meet crop requirements.

2.2.8.10 Sulfur (S)

2.2.8.10.1 Deficiency Symptoms

Sulfur-deficient plants are stunted and have stout, short stems and yellow foliage. Mild deficiencies in young crops cause whole plants to change color from pale green to yellow-green. In more mature crops or if the deficiency persists and becomes severe, older leaves are pale green and younger leaves are yellow. Sulfur deficiency reduces grain yield because affected plants produce fewer, smaller ears with fewer kernels. The grain may be low in protein because S is required for the formation of amino acids used in protein synthesis.

Yellow young leaves: Because S is not readily transferred from old to young leaves, symptoms develop first and are more severe on young leaves. Symptoms begin with all leaves turning pale green; the young leaves are the palest. Young leaves then turn pale yellow while old leaves remain pale green. The veins and interveinal tissues usually turn pale yellow, but in some varieties, the veins in the lower halves of the leaves may remain pale green during the early stages of deficiency.

Red-purple suffusion on leaves: On severely deficient young plants, red-purple color sometimes develops as a suffusion over the yellow areas of the youngest leaves and red striping may develop on the sheaths of old leaves.

2.2.8.10.2 Problem Soils

Sulfur deficiency is likely to occur in:

- Soils low in organic matter after many years of cropping
- Soils formed from parent material low in S (for example, certain volcanic rocks and ash)
- Acid sandy soils from which sulfates have been leached

2.2.8.10.3 Correcting Deficiency

Soil applications of any S fertilizer will correct deficiencies. Elemental S (flowers of S) can be broadcast and thoroughly mixed into the soil about 4 months before sowing. Gypsum (calcium sulfate) is another useful source of S. Tests can measure the amounts of available sulfate in the soil before sowing and predict the amounts of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

Sulfur deficiency in existing crops can be corrected by applying soluble sulfate salts, such as magnesium, ammonium, or potassium sulfate, in irrigation water. Foliar sprays of similar salts are usually not recommended because of the large numbers needed to meet crop requirements.

2.2.8.11 Zinc (Zn)

2.2.8.11.1 Deficiency Symptoms

Zinc-deficient corn crops often appear patchy. Within Zn-poor areas, plants can be very stunted and have short, stout stems and pale green to yellow foliage. Zinc deficiency affects both ear and tassel development. Affected crops produce small ears that set few grains. Tassels are often distorted and may be devoid of pollen when the deficiency is very severe. As a result, grain yields are severely reduced even by mild deficiencies.

White bands in younger leaves: Because Zn is not readily transferred from old to young leaves, symptoms develop first and are more severe on young leaves. Often, the youngest leaves are the most severely affected. Old leaves usually remain green and appear healthy. The youngest leaves turn pale green. White to yellow bands or streaks appear between the margins and mid-veins in the lower halves of the leaves. Eventually, the affected tissue dies and turns pale grey, leaving the margins and mid-veins green.

Zinc deficiency prevents elongation of the internodes. This causes the stems to become stout and flattened. As the lower leaf sheaths pull away from the stems, the plants often assume a fan-shaped appearance with the leaves crowded together at the tops.

2.2.8.11.2 Problem Soils

Zinc deficiency is likely to occur in:

- Strongly alkaline soils with depressed Zn availability
- Leached sandy soils with low total Zn
- Leveled soils that may have Zn-deficient subsoils exposed on their surfaces
- Soils in which heavy applications of phosphate fertilizers may reduce crop use of Zn

2.2.8.11.3 Correcting Deficiency

Foliar and soil applications of Zn salts have been used to correct deficiencies. Soil applications of zinc chelates, sulfates, or oxides should be broadcast and mixed into the soil 2 to 3 months before sowing. Soil applications are effective for 6 to 8 years before fresh applications may be needed.

Foliar sprays exert no residual effects and fresh applications must be made to each crop. Best results are obtained when a 0.5 to 1% solution of a soluble Zn salt (for example, 0.5 to 1 kg zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$) per 100 L of water per ha) is applied 2 to 3 weeks after seedling emergence. Additional sprays should be applied as soon as symptoms reappear.

Soil tests can be used to estimate the amounts of available Zn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

TABLE 2.31
Key to Nutrient Deficiency Symptoms of Corn

Symptom	Deficient Nutrient
Color changes in lower leaves	
Yellow discoloration from tip backward in form of a V	Nitrogen
Brown discoloration and scorching along outer margin from tip to base	Potassium
Yellow discoloration between veins; edges become reddish-purple	Magnesium
Purpling and browning that extend in waves backward from tip	Phosphorus
Uniform yellowing of upper and lower leaves	Sulfur
Color changes in upper leaves	
Emerging leaves show yellow to white bleached bands in lower parts of leaves	Zinc
Young leaves show interveinal chlorosis along entire length	Iron
Young leaves are uniformly pale and yellow; older leaves die starting from the tips	Copper
White, irregular spots between veins	Boron
Young leaves show pale green to yellow discoloration between veins	Manganese
Young leaves wilt and die along the margins	Molybdenum

Note: Stunted plants and loss of green color are common for all deficiencies.

2.2.8.12 Salinity

2.2.8.12.1 Problem Soils

TABLE 2.32
Effects of Salinity on Corn[1]

Appearance	Causal Condition
Unthrifty, low-yielding crops	When sodium chloride (NaCl) is only moderately toxic, affected plants have a droughty appearance and grow poorly. As the toxicity becomes more severe, plants become stunted and develop short, thick stems and erect, grey-green foliage. Although the number of ears developed may not be affected, ear and kernel sizes are reduced and affected crops usually produce less grain than normal.
Droughty appearance	Sodium chloride is carried in the transpiration stream and accumulates to high concentrations in old leaves. Symptoms appear first in old leaves and work up the plant to younger leaves if the toxicity persists. Affected plants have harsh, droughty appearance. Foliage is dull grey-green and leaves are shorter and held more erect than normal. The margins of all leaves are often rolled in, as if the leaves had wilted.
Weather-tipped older leaves	As the toxicity develops, grey necrosis appears on the margins near the tips of old leaves. The necrosis spreads down the leaves, usually along the margins, making them appear weather-tipped.

Sodium cloride toxicity is more likely to occur in:

- Saline soils formed from salt water sediments
- Previously fertile soils flooded or heavily irrigated with water containing a high concentration of NaCl

2.2.8.12.2 Correcting Toxicity

Leaching with good quality irrigation water is the most effective means of removing excess Na and Cl from soil. The water table may have to be lowered to make the treatment effective. Permeable soils such as well structured sandy soils are often easily reclaimed, but the problem is more difficult in less permeable soils such as poorly structured heavy clays.

If exchangeable Na in the soil is high, reclamation involves replacement of the adsorbed Na by Ca via application of gypsum (calcium sulfate) and then leaching the dissolved Na and Cl beyond the rooting depths of the plants. If irrigation water is to be used to leach the Na, the quality of the water should be checked before use to make sure it is not saline. Where excess NaCl cannot be wholly corrected by soil leaching, a more tolerant species may have to be grown.

2.2.8.13 Manganese Toxicity[1]

2.2.8.13.1 Problem Soils

TABLE 2.33
Effects of Manganese Toxicity on Corn

Appearance	Causal Condition
Unthrifty, low-yielding crops	On some soils or under certain conditions, soluble Mn can reach levels that are toxic for plant growth. In corn, such toxicity causes stunted plants with thin stems and yellow-green foliage. Grain yield is depressed, mainly by reducing the numbers and sizes of ears produced. If the toxicity is very severe, small, distorted plants that produce little grain or die before maturity may develop.
Interveinal chlorosis on older leaves	Excess Mn accumulates in older tissues and symptoms appear first and are usually more severe on old leaves. However, if the toxicity persists, symptoms spread rapidly to young leaves until entire plants are affected. Leaves turn pale green and pale yellow flecks and mottles develop between the veins in the mid-sections of the leaves. The chlorotic tissue dies, turns pale brown or grey, and the lesions join to produce streaks of necrotic tissue running between the veins in the mid-sections of the leaves.
Weather-tipped older leaves	When the deficiency persists, the margins and tips of old leaves turn dark grey-green, then brown. The mid-veins and surrounding tissues appear silver-green and the dead brown tips appear weather-tipped.

Manganese toxicity is likely to occur in:

- Strongly acid soils with increased solubility of Mn
- Waterlogged soils in which poor aeration causes unavailable manganic (Mn^{3+}) ions to be reduced to manganous (Mn^{2+}) ions that can be taken up by plants

2.2.8.13.2 Correcting Toxicity

Manganese toxicity is usually corrected by adopting management practices that reduce the levels of soluble Mn in soils. If soils are strongly acid, liming to an alkaline reaction will reduce excessive levels of soluble Mn. Drainage of waterlogged soils prevents anaerobic conditions in which soluble Mn^{2+} ions are produced. If soils have been over-fertilized with Mn^{2+}, heavy leaching with low Mn irrigation waters or mulching with organic materials will remove soluble Mn from the soil solutions.

2.2.8.14 Nutrient Element Plant Tissue Status

TABLE 2.34
Critical Plant Nutrient Element Levels in Corn Leaves Opposite to and below the Ear at Tasseling

Major Element	%	Micronutrient	ppm
Nitrogen	2.90	Boron	10
Phosphorus	0.25	Copper	5
Potassium	1.90	Iron	25
Calcium	0.40	Manganese	15
Magnesium	0.15	Zinc	15
Sulfur	0.15		

TABLE 2.35
Normal Expected Ranges in Nutrient Elements Concentrations for Parts of Corn Plants

	Average Range in Concentration				
Element	Whole plant at 3- to 4-leaf stage	Ear leaf at silk	Stalk at silk above ear node	Stalk at silk below ear node	Grain at maturity
			g/kg		
Nitrogen	35–50	27–365	—	—	10–25
Phosphorus	4–8	2–4	1–2	1–2	2–6
Potassium	35–50	17–25	10–20	20–30	2–4
Calcium	9–16	4–10	1–3	1–3	0.1–0.2
Magnesium	3–8	2–4	1–3	1–3	0.9–2.0
Sulfur	2–3	1–3	—	—	—
			mg/kg		
Aluminum	100–200	10–200	10–25	50–100	—
Boron	7–25	4–15	4–12	4–9	1–10
Barium	—	0.50	5–20	2–15	—
Copper	7–20	3–15	3–15	3–10	1–5
Iron	50–300	50–200	50–75	50–100	30–50
Manganese	50–160	20–250	20–70	50–100	5–15
Sodium	—	1–400	1–100	1–100	—
Strontium	—	10–100	10–50	10–30	—

TABLE 2.36
Sufficiency Ranges for Major Elements and Micronutrients in Corn Plants

	Time of Sampling and Plant Part		
Element	**15 whole tops of plants 12 in. tall**	**12 leaves below whorl prior to tasseling**	**12 ear leaves at initial silk**
		%	
Nitrogen	3.50–5.00	3.00–5.00	2.70–4.00
Phosphorus	0.30–0.50	0.25–0.45	0.25–0.50
Potassium	2.50–4.00	2.00–2.50	1.70–3.00
Calcium	0.30–0.70	0.25–0.50	0.21–1.00
Magnesium	0.15–0.45	0.13–0.30	0.20–1.00
Sulfur	0.15–0.50	0.15–0.50	0.21–0.50
		ppm	
Boron	5–25	4–25	5–25
Copper	5–20	3–15	6–20
Iron	50–250	10–100	20–250
Manganese	20–300	15–300	20–200
Molybdenum	0.10–10.0	0.10–0.30	0.10–0.20
Zinc	20–60	15–60	25–100

Source: Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide, 1996, MicroMacro Publishing, Athens, GA.

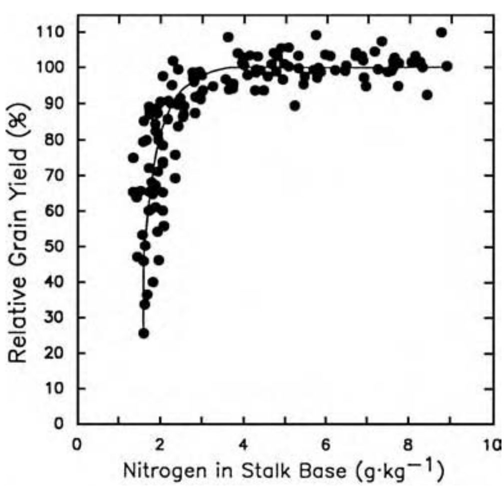


FIGURE 2.12 Relative yield of corn grain versus concentration of total nitrogen in a basal segment of a stalk.

2.2.9 Chlorophyll Meter Readings of Corn Leaves[2]

Chlorophyll meter readings taken in the field are compared to the average readings from a high N reference area. The field to be tested should have received no fertilizer N beyond a normal amount of starter N and the N applied to the high N reference area.

The manual accompanying the chlorophyll meter should provide detailed instructions for operating the meter. What follows is a brief explanation of how to use a chlorophyll meter to take leaf readings for an early season test:

Internal calibration — This is the first step in the procedure. Turn the meter on. *CAL* will appear in the window. With no sample in the sample slot, press the measuring head down. The meter will beep when calibration is complete. The display will then show *N = 0* (*N* is the sample number). If the display flashes *CAL* and beeps, the calibration was not performed correctly, probably because the sample head was not closed completely. Repeat the procedure. If the meter beeps and *EU* appears at the top of the display, the top and bottom windows of the measuring head may be dirty. Wipe them clean and repeat the procedure.

Leaf reading — Place a leaf in the slot of the meter head. Use the center line on the measuring head to align the measuring head window and the spot on the leaf to be read. When the head is closed on the leaf, the meter will beep, a digital reading will appear on the display, and the reading will be stored in the meter. Sometimes the meter will beep and not give a reading. When this happens, try changing the alignment of the leaf slightly before closing the head again.

Standardization — Meter readings of corn leaves are affected by the part of the leaf and the position of the leaf on the plant that is sampled. Therefore, it is necessary to standardize the part of the corn plant to be read with the chlorophyll meter. For this test, chlorophyll meter readings should always be done on leaf 5 of a plant to be tested. The reading is done at a point on the leaf approximately 1/2 inch from the edge of the leaf and 3/4 of the length of the leaf from the leaf base. Do not take readings on the midrib or too near the edge.

Pick representative plants in the field for meter readings. Care should be taken to avoid unusual or damaged parts of leaves when reading the chlorophyll meter. Plants chosen should be relatively evenly spaced rather than separate from others or in clusters. Use your body to shield the meter from direct sunlight. Wet leaves may be read if beaded water is shaken or rubbed off before the leaf is inserted into the meter.

Questionable readings — Occasionally you may get readings that seem incorrect or are very different from others in the field. Such a reading can be deleted by pressing the *1 DATA DELETE* button to remove the last reading. Be careful not to press *ALL DATA CLEAR* because it will delete all readings taken to that point. If you want to look over all of existing readings at any time, use the *DATA RECALL* button to scan them. During the scan, you may use the *DELETE* button to remove a reading and then replace it by taking another reading.

Determining average — A chlorophyll meter will store up to 30 readings. At any point, pressing the *AVERAGE* button will display the average of the readings taken. When you are ready to begin a new set of readings, press *ALL DATA CLEAR* to delete all the readings saved to that point.

Once an operator is familiar with meter operation and leaf stage identification, readings can be done very quickly. Since the meter memory will store up to 30 readings and calculate an average, at least 30 readings should be taken. If a field is very variable, more readings may be necessary for an accurate field average or to determine whether several different N rates would be appropriate. At least 25 to 30 readings should be taken from plants in the high N reference sections.

Advantages of early season chlorophyll meter testing —

- Chlorophyll meter readings are quick, easy, and provide instantaneous values.
- No samples need to be collected, processed, and sent to a laboratory for analysis.
- The only cost of sampling is labor.
- Nitrogen recommendations are accurate (comparable to the pre-side-dress soil nitrate test).

Disadvantages of early season chlorophyll meter testing —

- Initial expense is high; the meter costs about $1,400.
- Early season corn leaf chlorophyll levels are affected by hybrid selection and environmental stresses. Thus, high N reference plots must be established.
- This test is not applicable to fields that have received preplant or at-plant N fertilizer applications beyond starter N.

2.2.10 Planting Rates

TABLE 2.37
Corn Plants/Acre at Various Planting Rates

Distance between Rows	Checked Corn			Drilled Corn			
	2/hill	3/hill	4/hill	8 in.	10 in.	12 in.	14 in.
2 ft. 8 in.	24,502	19,600	16,335	14,001			
2 ft. 10 in.	23,061	18,449	15,374	13,178			
3 feet	9,680	14,520	19,360	21,780	17,424	14,520	12,447
3 ft. 2 in.	8,690	13,030	17,380	20,634	16,507	13,756	11,791
3 ft. 4 in.	7,840	11,760	15,680	19,602	15,682	13,068	11,201
3 ft. 6 in.	7,110	10,670	14,220	18,669	14,935	12,446	10,688
3 ft. 8 in.	17,820	14,256	11,880	10,183			
3 ft. 10 in.	17,045	13,636	11,363	9,740			

2.2.11 Correction Tables

TABLE 2.38
Corn Grain Moisture Yield Correction

% Moisture	lb Ears to Equal 1 bu	% Moisture	lb Ears to Equal 1 bu
14	66.9	25	81.3
15	67.9	26	82.8
16	68.9	27	84.2
17	70.0	28	85.6
18	71.3	29	87.0
19	72.6	30	88.5
20	74.0	31	89.9
21	75.4	32	91.4
22	76.8	33	92.9
23	78.3	34	94.3
24	79.8	35	95.7

TABLE 2.39
Percentage of Shelled Corn to Add or Subtract to Correct to 15.5% Moisture Content

% Moisture in Corn	% to Add	% Moisture in Corn	% to Subtract	%Moisture in Corn	% to Subtract
10.5	5.9	15.5	0.0	20.5	5.9
11.0	5.3	16.0	0.6	21.0	6.5
11.5	4.7	16.5	1.2	22.0	7.7
12.0	4.1	17.0	1.8	23.0	8.9
12.5	3.6	17.5	2.4	24.0	10.1
13.0	3.0	18.0	3.0	25.5	11.8
13.5	2.4	18.5	3.6	30.5	17.8
14.0	1.8	19.0	4.1	35.5	23.7
14.5	1.2	19.5	4.7	40.5	29.6
15.0	0.6	20.0	5.3	50.5	41.4

2.2.12 Weights and Measures

Conversion factor — 1 bu (56 lb) shelled corn is approximately equal to 2 bu (70 lb) husked ear corn.

TABLE 2.40
Weights and Measures of Corn Commodities

	Approximate Net Weight		
Commodity	Unit	lb	kg
Ear, husked	bu	70	31.8
Shelled	bu	56	25.4
Meal	bu	50	22.7
Oil	gal	7.7	3.5

TABLE 2.41
Weight of Grain and Standard Yield of Level Full Bushel of Corn

Weight (lb) of 1 Measured bu	Multiplication Factor to Yield 1 Standard bu Shelled Corn
60	1.07
58	1.04
56	1.00
54	0.96
52	0.93
50	0.89
48	0.86
46	0.82
44	0.79
42	0.75
40	0.71

TABLE 2.42
Corn Seeds per Pound, Weight per Bushel, and Germination Time

Corn Seeds/lb (1,000)	Seeds/g (no.)	Weight/bu	Germination Time (days)
62	3	56	7

REFERENCES

1. Grundon, N.J., *Hungry Crops: A Guide to Nutrient Deficiencies in Field Crops,* 1987, Information Series QI87002, Queensland Department of Primary Industries, Brisbane, Australia.
2. *The Early-Season Chlorophyll Meter Test for Corn*, 1997, Agronomy Facts 53, Pennsylvania State University, University Park, PA.

2.3 GRAIN SORGHUM [*Sorghum bicolor* (L.) *Moench]*

2.3.1 Introduction

Some question surrounds whether the early cultivation of sorghum began in the Nile Valley or elsewhere in Africa, but its domestication is certainly tied to the origin and evolution of African agriculture. Sorghum is known as sorgho in France, sorgo in Spain and Italy, mohrenhirse and sorghum in Germany, jowar in India, and durra in Arabian countries. The five races of grain sorgum are *bicolor*, *guinea*, *caudatum*, *kafir*, and *durra*.

Sorghum has a wide range of uses: as grain, sweetener (sugar sorghum), animal feed, silage, fuel, building material, and in broom making. Sorghum can grow at rainfall levels over 250 mm, but grows best with 800 to 1,200 mm of rain during the vegetative season. Under very dry conditions, recommended densities range from 0.5 to 3 plants per m^2 under dry conditions to 10 plants per m^2 when irrigated or grown for forage. Seed germinates at temperatures >15°C, with optimum growth between 25 and 30°C. Early maturing varieties can be harvested 3 to 4 months after sowing and late varieties, 8 to 10 months after sowing. Sorghum can grow on light sandy soils, but best yields are obtained from high fertility soils.

2.3.2 Production Statistics

TABLE 2.43
U.S. Sorghum Grain and Silage Acreage, Yield, and Production, 1991–2000.[a]

	Sorghum for Grain[b]			Sorghum for Silage		
Year	Harvested Acres (1,000)	Yield (bu/acre)	Production (1,000 bu)	Harvested Acres (1,000)	Yield (tons/acre)	Production (1,000)
1991	9,670	59.3	584,860	463	10.0	4,846
1992	12,050	72.6	675,022	453	12.1	5,468
1993	6,916	59.9	534,172	351	11.2	3,914
1994	8,882	72.7	645,741	362	11.9	4,316
1995	6,253	55.6	458,648	413	10.3	4,242
1996	11,811	67.3	795,274	423	11.8	4,976
1997	9,158	69.2	633,545	412	13.1	5,365
1998	7,723	67.3	519,933	306	11.4	3,526
1999	6,544	69.7	595,166	320	11.6	3,716
2000[c]	7,723	60.9	470,070	265	10.8	2,663

[a] Grain and sweet sorghum for all uses including syrup.
[b] Includes both sorghum for grain, and sweet sorghum forage or seed.
[c] Preliminary.

Source: Crops Branch, National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 2.44
U.S. Grain Sorghum Acreage and Production, 2000

State	Area Harvested (1,000 acres)	Yield (bu/acre)	Production (1,000 bu)
Kansas	3,200	59	188,800
Texas	2,350	61	143,350
Maryland	756	84	756
Arizona	720	80	720
California	600	75	600
Nebraska	500	70	35,000
U.S. Total	7,723	60.9	470,070

Source: Crops Branch, National Agricultural Statistics Service, Washington, D.C., 2001.

TABLE 2.45
U.S. Utilization of Sorghum for Silage, 2000

State	Area Harvested (1,000 acres)	Yield (tons/acre)	Production (1,000 tons)
Kansas	65	10	650
Texas	60	10	600
Nebraska	20	11	220
South Dakota	20	9	180
Oklahoma	17	12	204
Georgia	15	9	135

Source: Crops Branch National Agriculture Statistics Service, Washington, D.C., 2001.

2.3.3 Characteristics of Growth

TABLE 2.46
Stages of Growth of Grain Sorghum

Stage	Days after Emergence[a]	Stage Name and Description
0	0	Emergence — usually occurs 3 to 10 days after planting.
1	10	Three-leaf stage — three fully developed leaves; collar of each leaf is visible without tearing the blade or sheath; the growing point or meristem is still below the soil surface.
2	20	Five-leaf stage — five leaves are fully developed; the root system is developing rapidly; disease at lower nodes may cause loss of leaves at the nodes; rate of growth is increased and remains almost constant until physiological maturity.
3	30	Stage has no descriptive name; plant normally has 7 to 10 fully developed leaves; reproductive development is initiated; the final number of leaves has been determined; potential panicle size will be established; three lower leaves may be lost; culm or stalk growth is rapid.
4	40	Stage has no descriptive name; flag leaf is visible in the whorl; all leaves except the final three or four are fully expanded; 80% of total leaf area is present, light interception is approaching maximum; reference to the number of leaves or leaf number should be from the top; because a variable number of leaves were lost from the base of the culm, the flag leaf is numbered 1; about 20% of the final dry weight is present.
5	50	Boot — leaves are fully expanded; panicle is near full size and enclosed in the flag leaf sheath; culm elongation is essentially complete; peduncle elongation begins; boot stage of inflorescence development occurs during this stage.
6	60	Half-bloom — peduncle has grown rapidly during stage 5 and the panicle is extended from the flag leaf sheath; half the plants in a field are in some stage of bloom; for some, flowering has progressed half-way down the panicle; time required to reach half bloom depends upon maturity of the hybrid and environmental conditions.
7	70	Soft-dough — between stage 6 and the point at which grains are at soft-dough stage, about half the total dry weight of the grain is accumulated; culm weight is decreased by about 10% during grain filling; lower leaves continue to be lost and only 8 to 12 functional leaves remain.
8	85	Hard-dough — About 75% of the grain dry weight has accumulated; grain contents are more solid; culm weight has declined to its lowest dry matter weight.
9	95	Physiological maturity — Plant and panicle reach maximum total dry weight; the time from flowering to physiological maturity varies by hybrid but represents about a third of the total time from planting; grain moisture is usually 25 to 35%; remaining functional leaves may remain green; branches may develop from upper nodes if temperature and moisture are adequate.

[a] Approximate number of days for hybrids of RS 610 maturity grown at Manhattan, KS.

Source: Growth stages of sorghum, *Agron J.*, 64, 13, 1972.

2.3.4 Sorghum Grain Characteristics

TABLE 2.47
Nutritive Values of Whole Sorghum Grain

Component	Value
Calories/100 g	332
Protein, %	11.0
Fat, %	3.3
Total calcium, mg/lb	28
Total phosphorus, mg/lb	287
Total potassium, mg/lb	350
Carbohydrates, %	73.0

TABLE 2.48
Levels and Degrees of Toxicity of Prussic Acid in Grain Sorghum

Level (ppm dry weight)	Relative Degree of Toxicity
0–250	Very low (safe to pasture)
250–500	Low (safe to pasture)
500–750	Medium (doubtful to pasture)
750–1,000	High (dangerous to pasture)
>1,000	Very high (very dangerous to pasture)

Source: *Modern Grain Sorghum Production,* 1990, Iowa State University Press, Ames.

TABLE 2.49
Levels and Degree of Toxicity of Nitrates in Grain Sorghum

Nitrate-Nitrogen Content (ppm dry weight)	Toxicity
0–1,000	Safe under all feeding conditions
1,000–1,500	Safe for all except pregnant animals
1,500–4,000	Risk of poisoning: should not constitute more than 50% of ration
>4,000	Potentially toxic: should not be fed

Source: *Modern Grain Sorghum Production,* 1990, Iowa State University Press, Ames.

TABLE 2.50
Average Mineral Composition of Grain Sorghum

Element	Content (%)
Nitrogen	1.80
Phosphorus	0.30
Potassium	0.40
Sulfur	0.15
Calcium	0.04
Magnesium	0.15
Iron	0.005
Manganese	0.001
Copper	0.001

Source: *Modern Grain Sorghum Production*, 1990, Iowa State University Press, Ames.

TABLE 2.51
Influence of Nitrogen Application on Protein Content of Grain Sorghum

Nitrogen Rate (lb/acre)	Yield (lb/acre)	Protein (%)
0	3,100	6.8
40	4,300	6.9
80	5,100	7.8
160	6,200	10.3
320	6,500	12.4

Source: *Modern Grain Sorghum Production*, 1990, Iowa State University Press, Ames.

TABLE 2.52
Quality Components of Sorghum Grain

Component	Content
Digestible energy, kcal/kg	3,453
Protein, %	11.0
Lysine, %	0.27
Methionine + cystine, %	0.27
Tryptophan, %	0.09
Calcium, %	0.04
Phosphorus, %	0.30
Fiber, %	2.0
Ether extract, %	2.8

Source: *Modern Grain Sorghum Production*, 1990, Iowa State University Press, Ames.

2.3.5 Sorghum Plant Nutrition

TABLE 2.53
Nutrient Element Contents of Above-Ground Parts of Grain Sorghum Plant

Yield (lb/acre)	Plant Part	Dry Matter (lb)	N (lb)	P_2O_5 (lb)	K_2O (lb)	Ca (lb)	Mg (lb)	S (lb)
6,000	Grain	5,100	95	30	25	3	10	7
	Stover	6,800	70	12	100	15	8	13
8,000	Grain	6,800	120	60	30	5	14	10
	Stover	8,000	80	16	120	20	12	10
10,000	Grain	8,500	145	70	35	7	18	13
	Stover	9,500	95	20	135	25	20	18

Source: *Modern Grain Sorghum Production,* 1990, Iowa State University Press, Ames.

TABLE 2.54
Normal Ranges in Composition of Leaves and Grain of Grain Sorghum

Element	Range	
	Leaf	Grain
	%	
Nitrogen	2.0–3.0	1.0–2.0
Phosphorus	0.2–0.4	0.2–0.4
Potassium	1.5–3.0	0.3–0.5
Calcium	0.3–0.5	0.03–0.05
Magnesium	0.2–0.4	0.1–0.2
	ppm	
Boron	10–75	1–3
Copper	5–10	5–15
Iron	15–150	40–60
Manganese	10–100	5–15
Zinc	10–75	5–15

Source: *Modern Grain Sorghum Production,* 1990, Iowa State University Press, Ames.

TABLE 2.55
Critical Nutrient Element Concentrations for Grain Sorghum[a]

Nutrient Element	Concentration
	%
Nitrogen	2.40
Phosphorus	0.20
Potassium	2.20
Calcium	0.40
Magnesium	0.25
	ppm
Boron	15
Copper	5
Iron	25
Manganese	15
Molybdenum	0.2
Zinc	15

[a] Based on the leaf immediately below the flag leaf during booting and flowering.

Source: *Modern Grain Sorghum Production*, 1990, Iowa State University Press, Ames.

2.3.6 Nutrient Element Uptake by Grain Sorghum

TABLE 2.56
Approximate Amounts of Nutrient Elements Removed by 5,600 Pounds Grain Sorghum

Element	Grain (lb)	Stover (lb)[a]
Nitrogen	90	76
Phosphorus as phosphate	35	20
Potassium as potash	22	110
Sulfur	9	10
Magnesium	7	10
Calcium	1.4	18.9
Copper	0.014	0.02
Manganese	0.056	0.11
Zinc	0.07	0.14

[a] The amount of stover is not linearly related to grain yield.

Source: Adapted from *Changing Patterns in Fertilizer Use*, 1968, Soil Science Society of America, Madison, WI.

TABLE 2.57
Fertilizer Nutrient Element Demand/Uptake/Removal (kg/ha) by Grain Sorghum

	kg/ha		
Plant Condition	Nitrogen	Phosphorus as Phosphate	Potassium as Potash
Dryland, low yield	40	20	40
Wet, medium yield	60	35	75
Irrigated, high yield	100	50	125
Green forage	80	30	70
Silage	150	40	150
Top yield, grain and forage	250	60	250

Source: *IFA World Fertilizer Use Manual.,* 2000, International Fertilizer Industry Association, Paris.

TABLE 2.58
Cumulative Estimated Amounts of Primary Nutrient Elements Absorbed by Grain Sorghum during the Georgia Growing Season (5,600 lb/acre)

	Stage of Growth				
Nutrient Element	0–2	3	5	8	9
Nitogen, %	5	38	70	85	100
Phosphorus as phosphate, %	3	27	60	87	100
Potassium as potash, %	8	48	80	95	100
Nitrogen, lb	5	38	70	85	100
Phosphorus as phosphate, lb	2	16	36	52	60
Potassium as potash, lb	6	38	64	76	80

TABLE 2.59
Nutrient Element Utilization by Grain Sorghum Crop (8,000 lb/acre)

Nutrient Element	Uptake (lb/acre)
Nitrogen	250
Phosphorus as phosphate	90
Potassium as potash	240
Magnesium	44
Sulfur	38

TABLE 2.60
Key to Nutrient Element Deficiencies for Sorghum

Symptom	Deficiency
Color changes in lower leaves	
Yellow discoloration extending from tip backward in form of V along midrib	Nitrogen
Brown discoloration or firing along outer margin from tip to base	Potassium
Purpling and browning from tip backward; in young plants entire plant shows general purpling	Phosphorus
Color changes in upper leaves	
Yellow to white bleached bands appear on lower parts of emerging leaves	Zinc
Entire lengths of young leaves show interveinal chlorosis; leaves may eventually turn white	Iron
Uniform yellowing of upper leaves	Sulfur

Note: Stunted plants and loss of green color are common to all deficiencies.

Source: *Modern Grain Sorghum Production,* 1990, Iowa State University Press, Ames.

2.3.7 Nutrient Element Deficiencies[1]

2.3.7.1 Boron (B)

2.3.7.1.1 Deficiency Symptoms

Boron-deficient crops are very stunted, lack vigour and yield poorly. Affected plants have short, stout stems and dark green foliage. Leaves are shorter and held more erect than usual. Deficient plants produce small heads that may be partly barren, resulting in low grain yields.

White interveinal lesions on younger leaves: Because B is not readily transferred from old to young leaves, symptoms appear first and are more severe on young leaves. Old leaves usually remain green and appear healthy. The youngest leaves remain dark green but develop intermittent, white interveinal lesions, often over their entire lengths. Tissue next to such lesions is brittle and easily torn. The edges of the torn laminae may turn brown but necrosis of the remaining tissue is rare.

Fan-shaped stems: Because B plays a role in the elongation of internodes and leaves, stems on deficient plants are very short, often flattened or oval in cross-section, with leaves crowded together at the top. As the leaf sheaths pull away from the stem, they resemble a partly opened fan.

2.3.7.1.2 Problem Soils

Boron deficiency is likely to occur in:

- Soils derived from parent material low in B such as acid igneous rocks or freshwater sediments
- Sandy soils from which B has been leached by heavy rainfall

- Alkaline soils, especially those containing free lime
- Soils low in organic matter
- Acid peat and muck soils

2.3.7.1.3 Correcting Deficiency

Boron deficiency can be corrected by applying soil dressings or foliar sprays of fertilizers. Soil dressings are more effective if broadcast and mixed into the soil some months before sowing. Borax, boric acid, and chelated B compounds are suitable for soil application, but only boric acid and chelated B compounds are suitable for foliar sprays. Foliar sprays should be applied about 5 to 6 weeks after seedling emergence or as soon as symptoms appear. While soil dressings often remain effective for many years before fresh applications are needed, foliar sprays have little residual value and must be applied to every crop.

Tests can estimate the amount of available B in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

2.3.7.2 Calcium (Ca)

2.3.7.2.1 Deficiency Symptoms

Sorghum is very sensitive to Ca deficiency and even mild deficiencies can severely reduce growth and grain yields. Affected plants are stunted and have short, stout stems and dark green, often ragged foliage. If the deficiency is severe, whole plants may die or the heads may be malformed and partly or completely barren.

Malformed younger leaves: Because Ca is not readily transferred from old to young leaves, symptoms develop and are more severe on young leaves. Affected leaves are dark green, short, brittle, and held more erect than usual. Pale yellow chlorotic areas develop near the margins and these are easily torn, giving the leaves a malformed appearance.

Brown necrosis on younger leaves: If the deficiency persists, leaves missing sections of lamina may be produced. Tissue adjacent to the affected areas is usually chlorotic, then quickly dies and turns dark brown.

Flattened stems: Calcium deficiency prevents the elongation of the internodes. Affected plants have very short stems that are oval in cross-section. Leaves are crowded together at the top of the plants.

2.3.7.2.2 Problem Soils

Calcium deficiency is likely to occur in:

- Acid sandy soils from which Ca has been leached by heavy rainfall
- Strongly acid peat and muck soils that have low total Ca
- Sodic soils in which exchangeable Na and pH are high, thus depressing the Ca uptake
- Soils with high levels of soluble Al and low levels of exchangeable Ca

2.3.7.2.3 Correcting Deficiency

Calcium deficiency can be corrected by broadcasting a suitable fertilizer and mixing it into the soil some months before sowing. Where the chief problem is a lack of Ca, suitable fertilizers are gypsum (calcium sulfate) and calcium nitrate or chloride. However, if the soil pH is low, lime or limestone (calcium carbonate) and dolomite (a mixture of calcium and magnesium carbonates) are more suitable.

A soil test can be used to determine the lime or Ca requirement of a soil. However, since the correct rate of application depends on soil type and the crop to be grown, advice should be sought on fertilizer practices used on similar soils in the district. Excessive use of lime may induce K, Mg, Fe, Mn, Zn, or Cu deficiencies so care should be taken to prevent over-liming.

2.3.7.3 Copper (Cu)

2.3.7.3.1 Deficiency Symptoms

Mild deficiencies usually exhibit no clearly recognizable symptoms, but cause unthriftiness, delayed maturity, and stunted plants. Definite symptoms are associated with severe deficiencies only. Affected plants are very short and have thin, spindly stems, pale green foliage, and smaller heads on which many flowers are barren.

Weather-tipped younger leaves: Because Cu is not readily transferred from old to young leaves, symptoms develop first and are more severe on young leaves. Frequently, the youngest leaves are the most affected, while old leaves remain dark green and appear healthy. Symptoms develop on the youngest leaves before they are unrolled from the whorls. They turn pale green and pale yellow chlorosis develops at the tips. The chlorosis is followed rapidly by pale brown necrosis and both symptoms advance down the margins towards the bases. The dead leaf tips usually roll or twist tightly into tubes. This symptom is known as weather tipping.

2.3.7.3.2 Problem Soils

Copper deficiency is likely to occur in:

- Peat and muck soils in which organic matter ties up soluble Cu in forms less available to plants
- Alkaline soils in which total Cu is low
- Leached acid soils containing low total Cu
- Soils formed from rocks low in Cu

2.3.7.3.3 Correcting Deficiency

Foliar sprays and soil dressings of Cu salts such as copper sulfate (bluestone) or copper chelates will correct Cu deficiency. Soil dressings should be broadcast and mixed into the soil some weeks before sowing. However, soil dressings may fail to correct deficiencies in some seasons and symptoms may reappear. If this occurs, foliar sprays should be applied immediately.

A reliable remedy is to apply foliar sprays of 0.5 to 1% solutions of soluble Cu salts (for example, 0.5 to 1 kg copper sulfate per 100 L water per ha), the first to be applied 4 to 6 weeks after seedling emergence. Additional sprays should be applied as soon as symptoms reappear.

Tests can be used to estimate the amount of available Cu in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

2.3.7.4 Iron (Fe)

2.3.7.4.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Sorghum is relatively sensitive to Fe deficiency, and temporary environmental conditions such as waterlogging may cause symptoms to appear, then disappear when conditions return to normal. Prolonged or severe deficiencies produce stunted plants with thin, spindly stems and pale yellow foliage. Mild or temporary deficiencies usually have few effects on grain yields. However, prolonged or severe deficiencies reduce head size and the number of grains set per head and result in low grain yields.

Yellow interveinal chlorosis on younger leaves: Because Fe is not transferred from old to young leaves, symptoms develop first and are more severe on young leaves. The youngest leaves are usually the most affected. Old leaves remain dark green and appear healthy. Young leaves turn pale green and develop pale yellow interveinal chlorosis over their entire lengths. Veins remain dark green and prominent.

2.3.7.4.2 Problem Soils

Iron deficiency is likely to occur in:

- Alkaline soils that have low levels of soluble Fe
- Waterlogged soils
- Acid soils with excessively high levels of soluble Mn, Zn, Cu, or Ni that depress Fe uptake
- Sandy soils low in total Fe
- Peat and muck soils whose organic matter ties up Fe

2.3.7.4.3 Correcting Deficiency

While soil dressings of inorganic Fe salts, such as iron sulfates or chlorides, have corrected deficiencies in some soils, the applied Fe quickly becomes insoluble and less available to plants. Iron salts of various organic chelates have proved promising as soil dressings because the chelate keeps the Fe in solution. For acid soils, FeEDTA is the most effective chelate, while FeHEDTA and FeDTPA are best on neutral soils. FeEDDHA is best for alkaline soils. However, to be effective, large amounts of chelates may be required.

An equally effective remedy is to apply solutions of inorganic salts or chelates to the foliage (1% solutions or 1 kg salt per 100 L water per ha). Because Fe is so immobile in plants, sprays need to be applied every 10 to 15 days to provide Fe to new leaves. Advice on fertilizer practices used on similar soils in the district should be sought to obtain the best remedy for the affected crop under local conditions.

2.3.7.5 Magnesium (Mg)

2.3.7.5.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Magnesium-deficient crops are unthrifty, lack vigor, and yield poorly. Deficient plants are stunted and have short, thin stems and pale green to yellow foliage. Severely deficient plants usually produce small heads that set few grains; grain yields are severely reduced.

Interveinal chlorosis of older leaves: Because Mg is readily transferred from old to young leaves, symptoms develop first and are more severe on old leaves. Symptoms then advance up the plants to younger leaves if the deficiency persists. Young leaves usually remain pale green and appear healthy. Pale yellow interveinal chlorosis develops on the mid-sections of old leaves and and extends rapidly over their entire lengths. As the symptoms progress, the chlorosis darkens to yellow-orange. The veins remain green and easily seen.

Brown necrosis on older leaves: When a deficiency is very severe, irregular, linear, rust-brown necrotic lesions develop on and adjacent to the veins in the chlorotic tissues. Eventually these lesions join to form rust-brown streaks running almost the full lengths of affected leaves.

2.3.7.5.2 Problem Soils

Magnesium deficiency is likely to occur in:

- Acid sandy soils from which Mg has been leached
- Strongly acidic peat and muck soils whose total Mg is low
- Soils that have been over-fertilized with Ca (for example, with lime) or K

2.3.7.5.3 Correcting Deficiency

Magnesium deficiency on acid soils is corrected by broadcasting dolomite (a mixture of calcium and magnesium carbonates) onto the surface and mixing it into the soil some months before sowing. When the problem is strictly Mg deficiency, band applications of magnesium sulfate or chloride can be made at planting. A soil test can be used to estimate the amounts of soluble and exchangeable

Mg in soil and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Magnesium deficiency in existing crops can be corrected by applying soluble salts, such as magnesium sulfate, chloride, or nitrate, with irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to supply crop requirements.

2.3.7.6. Manganese (Mn)

2.3.7.6.1 Deficiency Symptoms

Patchy, low-yielding crops: Affected crops often appear patchy. Within the Mn-poor area, plants are very stunted and have thin, spindly stems and dark green foliage marked by red-brown necrotic areas. Affected plants produce small heads that set few grains and produce low yields. When the deficiency is very severe, many plants die before developing heads.

Interveinal white lesions on younger leaves: Because Mn is not readily transferred from old to young leaves, symptoms develop first and are more severe on young leaves. Old leaves remain dark green and appear healthy. Young leaves turn pale green and develop intermittent, white lesions between the veins around their mid-sections. If the deficiency persists, these lesions spread toward the base — not toward the tips.

Necrotic lesions on younger leaves: When a deficiency becomes severe, brown necrotic lesions develop in interveinal tissues adjacent to the white lesions. Initially, the main veins and leaf tips remain green. When the vein dies, the death of the leaf follows. In extreme deficiencies, young, still-unrolling leaves die, followed by the death of the main shoot.

2.3.7.6.2 Problem Soils

Manganese deficiency is likely to occur in:

- Strongly alkaline soils whose Mn is less available to plants
- Poorly drained peaty soils whose Mn is in forms less available to plants
- Strongly acid sandy soils whose soluble Mn has been leached by heavy rain
- Soils formed from rocks low in Mn

2.3.7.6.3 Correcting Deficiency

Foliar sprays and soil dressings of Mn salts and oxides have been used to correct Mn deficiencies. Soil dressings are more effective when broadcast and mixed into the soil some weeks before sowing. However, foliar applications have generally been more successful. One or more foliar sprays of 0.5 to 1% solutions of soluble Mn salts (for example, 0.5 to 1 kg of manganese sulfate per 100 L of water per ha) usually correct the deficiency, the first applied 5 to 6 weeks after seedling emergence. If the symptoms reappear, sprays should be repeated immediately. While soil dressings usually last 5 to 6 years before fresh applications are needed, foliar sprays must be reapplied to every crop.

Tests can estimate the amount of available Mn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

2.3.7.7 Nitrogen (N)

2.3.7.7.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Nitrogen-deficient crops are unthrifty, mature more slowly, and yield poorly. Deficient young plants are stunted and have thin, spindly stems and pale green foliage. In mature crops, affected plants have pale green upper leaves and pale yellow or brown lower leaves. Head size and the number of grains set per head are low. Because N plays a vital role in the formation of protein, grain from deficient plants may also be low in protein.

Pale yellow older leaves: Because N is readily transferred from old to young leaves, symptoms develop first and are more severe on old leaves and work up the stems to young leaves if the deficiency persists. Young leaves are pale green and smaller than usual. Old leaves turn pale green and develop pale yellow chlorosis at the tips. The chlorosis is followed by pale brown necrosis and both symptoms advance down the main veins creating V-notch patterns while the margins remain green. Eventually, affected leaves die and form thatches of dead leaves around the bases of the stems.

Red stems: Some varieties often develop red stripes on the lower stems and old leaf sheaths when the deficiency is very severe. The red color is more intense on areas exposed to sunlight.

2.3.7.7.2 Problem Soils

Nitrogen deficiency is likely to occur in:

- Sandy soils that have been leached by heavy rainfall or excessive irrigation
- Soils low in organic matter
- Soils with a long history of cropping whose supplies of N have been exhausted

However, even fertile soils may suffer temporary N deficiencies when double-cropped, heavily leached, or waterlogged.

2.3.7.7.3 Correcting Symptoms

Nitrogen deficiency is corrected by increasing the level of available N in the soil by fallowing, which allows organic N to be converted to mineral N; by growing cover or cash crops of legumes, which can fix atmospheric N_2; or by adding nitrogenous fertilizers. Suitable fertilizers are urea, gaseous ammonia or ammonium sulfate, nitrate, and phosphates. Crop growth depends on the amount of N already in the soil.

A soil test can measure the amount of total N or nitrate (NO_3)-N in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Nitrogen deficiency in existing crops can sometimes be corrected by applying soluble salts such as urea with irrigation water or as a foliar spray. Spray applications usually result in a rapid response of short duration, and additional sprays 10 to 14 days apart may be needed to supply enough N for crop.

2.3.7.8 Phosphorus (P)

2.3.7.8.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Sorghum is not a good indicator of P deficiency. Mild deficiencies cause unthriftiness and delayed maturity but exert no recognizable symptoms. If a deficiency is severe, plants are very stunted and have stout stems and dark green-purple foliage. Severely deficient plants produce small heads that set few grains.

Dark yellow older leaves: Because P is readily transferred from old to young leaves, symptoms develop first and are more severe on old leaves, working up the stems to younger leaves if the deficiency persists. Old leaves remain dark green and develop dark yellow chlorosis at the tips. The chlorosis is followed by dark brown necrosis and both symptoms advance down the leaves, usually along the margins. Eventually, affected leaves die and turn brown to form thatches of dead leaves around the bases of the stems. Young leaves remain dark green but may be shorter and more erect than usual.

Purple leaves and stems: In some varieties, purple pigmentation develops on old leaves, leaf sheaths, and lower stems. The colors are more intense on areas exposed to sunlight, developing on the upper surfaces of the leaves and on parts of the stems that are not protected by the leaf sheaths.

Clear areas on middle leaves: When a deficiency is very severe, some varieties develop clear, transparent-like areas between the margins and mid-veins in the mid-sections of middle leaves. These lesions do not increase in size as symptoms develop further.

2.3.7.8.2 Problem Soils

Phosphorus deficiency is likely to occur in:

- Soils low in organic matter
- Soils with a long history of cropping and exhausted P supplies
- Highly weathered, Fe-rich acid soils whose phosphate is fixed in less available forms
- Soils that have lost their topsoil through erosion
- Akaline soils whose P may be insoluble and less available.

2.3.7.8.2 Correcting Deficiency

Phosphorus deficiency can be corrected by applying fertilizers to the soil at or before sowing. Suitable fertilizers are single or triple superphosphates or ammonium phosphates. The growth of crops depends on the amount of water-soluble phosphate available and the rate of exchange between soluble and insoluble forms of P in the soil. Tests can estimate the available phosphate in a soil and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Phosphorus deficiency in existing crops can be corrected by applying soluble salts, such as ammonium phosphates, with irrigation water. Spray applications of similar salts are usually not recommended because of the large number of applications needed to supply crop requirements.

2.3.7.9 Potassium (K)

2.3.7.9.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Sorghum is a good indicator of K deficiency. Affected crops lack vigor, mature slowly, and yield poorly. Deficient plants are very stunted and have short, thick stems and pale green to bronze-yellow foliage. As the deficiency increases, old leaves develop marginal necrosis, often called firing. Affected plants develop small heads that set few grains.

Interveinal and marginal necrosis on older leaves: Because K is easily transferred from old to young leaves, symptoms develop first and are more severe on old leaves, working up the stems to younger leaves if the deficiency persists. In some varieties, mild deficiencies cause faint, pale yellow interveinal chlorosis to develop over the entire lengths of middle leaves, followed rapidly by intermittent, necrotic lesions concentrated near the leaf tips and margins. Severely deficient plants develop marginal necrosis on old leaves. The pale brown necrosis develops near the leaf tips and advances down the margins, leaving the main veins and surrounding tissues green. Eventually, entire leaves die and form thatches of dead leaves around the lower stems.

2.3.7.9.2 Problem Soils

Potassium deficiency is likely to occur in:

- Soils low in organic matter after many years of cropping
- Sandy soils formed from parent material low in K
- Light textured soils whose K has been leached by heavy rainfall

2.3.7.9.3 Correcting Deficiency

Potassium deficiency is corrected by applying potassium nitrate, sulfate, or chloride to the soil at or before sowing. Crop yield depends on the amount of water-soluble and exchangeable K in the soil. Tests can measure the available K in the soil and predict the amount of fertilizer needed.

The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Potassium deficiency in existing crops can be corrected by applying soluble K salts, such as sulfate, chloride, or nitrate, with irrigation water. The foliar application of similar salts is usually not recommended because of the large number of applications needed to supply crop requirements.

2.3.7.10 Sulfur (S)

2.3.7.10.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Mild deficiencies of S in young crops cause poorer growth and lack of color. Whole plants appear pale green. In more mature crops, the plants are short and have thin, spindly stems, pale green old leaves, and yellow young leaves. Mildly deficient plants may not suffer much yield loss, but the protein content of the grain may be lower than usual because S deficiency prevents the conversion of N into many proteins. If a deficiency is severe, plants often develop small heads that set few grains, and yields are greatly reduced.

Pale yellow younger leaves: Because S is not readily transferred from old to young leaves when a deficiency occurs, symptoms develop first and are more severe on young leaves. Frequently, the youngest leaves are the most severely affected. Old leaves usually remain green and appear healthy. Young leaves first turn pale green, then pale yellow. Entire leaves are affected and veins are never prominent.

2.3.7.10.2 Problem Soils

Sulfur deficiency is likely to occur in:

- Soils low in organic matter after many years of cropping
- Soils formed from parent material low in S (for example, volcanic rocks and ash)
- Acid sandy soils from which sulfates have been leached

2.3.7.10.3 Correcting Deficiency

The application of soil dressings of any S fertilizer will correct the deficiency. On alkaline soils, elemental S (flowers of S) may be broadcast and thoroughly mixed into the soil about 4 months before sowing. On neutral or acid soils, gypsum (calcium sulfate) is a useful source of S.

Soil tests can measure the amount of available sulfate in soil before sowing and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

Sulfur deficiency in existing crops can be corrected by applying soluble sulfate salts such as magnesium, ammonium, or potassium sulfate in irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to supply crop requirements.

2.3.7.11 Zinc (Zn)

2.3.7.11.1 Deficiency Symptoms

Patchy, low-yielding crops: Affected crops lack vigor, are unthrifty, yield poorly, and often appear patchy. Affected plants are stunted and have very short stems and pale green foliage. On mature plants, heads are smaller than usual and may be partly barren.

Pale yellow bands on younger leaves: Because Zn is not readily transferred from old to young leaves, symptoms develop first and are more severe on young leaves. The most severe symptoms appear on the youngest unrolling leaves (thus called *white buds*). Old leaves remain dark green and appear healthy. Young leaves turn pale green and broad bands of pale yellow

to white tissue develop between the green mid-veins and margins in the lower halves of the leaves.

Necrotic lesions on younger leaves: If a deficiency persists, the chlorotic areas die and turn pale brown. Initially, the mid-veins remain green but eventually they are affected and die.

Interveinal chlorosis and necrosis on middle leaves: When a deficiency is prolonged, middle leaves develop pale yellow interveinal chlorosis near their tips followed rapidly by pale brown interveinal necrosis that becomes general as the necrotic lesions join in the tip halves of the leaves.

Fan-shaped stems: Zinc deficiency prevents the elongation of internodes and leaves. As a result, stems are short, often flattened or oval in cross-section, with the leaves crowded at the top to produce a fan-shaped appearance.

2.3.7.11.2 Problem Soils

Zinc deficiency is likely to occur in:

- Strongly alkaline soils whose availability of Zn is depressed
- Leached sandy soils whose total Zn is low
- Leveled soils whose Zn-deficient subsoils may be exposed on the surface
- Soils in which heavy, frequent applications of phosphatic fertilizers may have reduced crop use of Zn

2.3.7.11.3 Correcting Deficiency

Foliar and soil applications of Zn salts have been used to correct deficiencies. Soil dressings of zinc chelates, sulfates, or oxides should be broadcast and mixed into the soil 2 to 3 months before sowing. While soil dressings of Zn have residual effects for 6 to 8 years before fresh applications are needed, foliar sprays have no residual effects and fresh applications must be made to each crop. Best results are obtained when a 0.5 to 1% solution of a soluble Zn salt (for example, 0.5 to 1 kg zinc sulfate heptahydrate per 100 L water per ha) is applied 2 to 3 weeks after seedling emergence. Additional sprays should be applied as soon as symptoms reappear.

Tests can estimate the amount of available Zn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

2.3.7.12 Salinity[1]

2.3.7.12.1 Deficiency Symptoms

Unthrifty, low-yielding crops: High levels of NaCl in soils or irrigation water cause unthrifty, low yielding crops. Affected plants are stunted and have short, stout stems and dull grey-green foliage. Plants often have a harsh, droughty appearance and leaves are shorter and more erect than usual. The plants develop small heads that set few grains and produce low grain yields.

Grey necrosis on older leaves: Because NaCl is carried in the transpiration stream, symptoms appear first and are more severe on older leaves. Symptoms work up the stems to young leaves if the toxicity persists. Young leaves usually remain green but may be shorter and more erect than usual. Old leaves turn dull green and appear wilted; their margins roll inward. As NaCl accumulates to toxic concentrations, the leaf tips and margins die and turn grey-green then pale brown. The dead tissue rolls into tubes.

2.3.7.12.2 Problem Soils

Sodium chloride toxicity is more likely to occur in:

- Saline soils formed from salt water sediments
- Previously fertile soils that were flooded or heavily irrigated with water containing high concentrations of NaCl

2.3.7.12.3 Correcting Toxicity

Leaching with good quality irrigation water is the most effective means of removing excess Na and Cl from the soil. The water table may have to be lowered. Permeable soils such as well structured sandy soils are often easily reclaimed, but the problem is more difficult in less permeable soils (for example, poorly structured heavy clays).

If exchangeable Na in the soil is high, reclamation involves replacing Na with Ca by applying gypsum (calcium sulfate) and then leaching the dissolved Na and Cl beyond the rooting depths of the plants. If irrigation water is to be used to leach the Na, the water quality should be checked before use to make sure it is not saline. If excess NaCl cannot be wholly corrected by soil leaching, a more tolerant species may have to be grown.

2.3.8 Weights and Measures

The net weight of 1 bu sorghum grain is approximately 56 lb or 25.4 kg.

TABLE 2.61
Weight and Standard Yield of Level Full Bushel of Sorghum

Weight of 1 bu (lb)	Multiplication Factor to Yield Standard bu
60	1.07
58	1.04
56	1.00
54	0.96
52	0.93
50	0.89
48	0.86
46	0.82
44	0.79
42	0.75
40	0.71

TABLE 2.62
Sorghum Seeds/Pound, Weight/Bushel, and Germination Time

Seeds/lb (1,000)	Seeds/g (no.)	Weight/bu (lb)	Germination Time (days)
15	33	56	10

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2.4 OATS (*Avena sativa* L.)

2.4.1 Introduction

The oat belongs to the grass family (Poaceae or Gramineae). The oat is known as avoine in French, avena in Spanish and Italian, and hafer in German. Oats were some of the earliest cereals cultivated by man. They were known in ancient China as early as 7000 B.C. The oat belongs to the same plant family as barley, corn, rice, and wheat. It has higher food values (rich in starch and high quality protein and a good source of vitamin B) than any other cereal grain. The grain is primarily used as livestock feed (90% in the U.S.) and processed for making oatmeal, oatcakes, cookies, and ready-to-eat breakfast foods. Oat straw is commonly used as animal bedding.

The chief kinds of oats are *common* (most commonly grown in the U.S.), *red*, *side*, and *hull-less*. Oats grow especially well in cool, moist climates, and on fertile soil. They may be autumn-sown (winter oats in areas with mild winters) or spring-sown.

Yields are dependent on rainfall and range from 1.5 tons per ha with 350 mm rainfall to a high of 6.5 tons per ha with 750 mm rainfall. At a yield of 5.0 tons per ha, ear density is 350 per m^2, with a single ear weight of 1.43 g. Average oat yield in the U.S. in 2000 was 64.2 bu per acre; the highest was 98.0 and the lowest was 42.0 bu per acre. The fertilizer elements required to produce a 3.5-ton per ha grain yield are 70 kg N per ha, 35 kg P_2O_5 per ha, and 105 kg K_2O per ha.

2.4.2 Production Statistics

TABLE 2.63
Harvested Area, Yield, and Production of Oats by Continents and Specified Countries, 1999–2000

Continent/Country	Harvested Area (1,000 ha)	Yield (metric tons/ha)	Production (1,000 metric tons)
		Continent	
North America	2,491	2.35	5,863
South America	720	1.47	1,058
Europe	1,934	3.16	6,115
Eastern Europe	1,149	2.21	2,541
USSR	5,634	1.10	6,195
Africa	840	0.17	148
Asia	501	1.20	602
Oceania	598	1.95	1,167
World Total	14,116	1.73	24,383
		Country	
Russia	4,500	0.98	4,400
Canada	1,398	2.60	3,641
U.S.	993	2.14	2,122
South Africa	700	0.06	45
Australia	578	1.89	1,092
Poland	572	2.53	1,446
Ukraine	530	1.43	760
China	500	1.20	600

Source: Foreign Agriculture Service, Washington, D.C.

TABLE 2.64
U.S. Oat Acreage, Yield, and Production, 1991–2000

Year	Area Harvested (1,000 acres)	Yield (bu/acre)	Production (1,000 bu)
1991	4,816	50.6	243,851
1992	4.496	65.4	294,229
1993	3,803	54.4	206,731
1994	4.008	57.1	228,844
1995	2,952	54.6	161,094
1996	2,655	57.7	153,245
1997	2,813	59.5	167,246
1998	2,755	60.2	165,981
1999	2,453	59.6	146,193
2000[a]	2,324	64.2	149,195

[a] Preliminary.

Source: Crops Branch, National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 2.65
Leading Oat-Producing States, 2000

State	Area Harvested (1,000 acres)	Yield (bu/acre)	Production (1,000 bu)
North Dakota	315	63.0	19,845
Minnesota	310	59.0	22,320
Wisconsin	280	62.0	19,040
South Dakota	220	64.0	13,420
Iowa	180	65.0	12,060
Pennsylvania	145	55.0	8,265
Texas	100	44.0	4,300
U.S. Total	2,324	64.2	149,195

Source: Crops Branch, National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 2.66
U.S. Total and Per Capita Civilian Consumption of Oat and Oat Products as Food, 1990–1999

Calendar Year[a]	Total Consumed (million bu)[b]	Per Capita Consumption of Food products (lb)
1990	75.3	6.5
1991	76.6	6.5
1992	77.4	6.5
1993	73.0	6.1
1994	70.0	5.8
1995	67.0	5.5
1996	63.0	5.1
1997	59.0	4.7
1998	59.0	4.5
1999[c]	58.8	4.5

[a] Data shown for marketing year, June 1 to May 3.
[b] Oats used in oatmeal, prepared breakfast foods, infant foods, and other food products.
[c] Preliminary.

Source: Economics Research Service, Washington, D.C., 2001. All figures are estimates based on data from private industry sources, the U.S. Department of Commerce, the Internal Revenue Service, and other government agencies.

TABLE 2.67
Leading Oat-Producing States and Provinces

State or Province	1,000 Short Tons
Alberta	1,734
Saskatchewan	794
Iowa	639
Minnesota	638
South Dakota	625
Wisconsin	609
Manitoba	357
Quebec	328
Ontario	310
North Dakota	309

2.4.3 Nutrient Element Characteristics

TABLE 2.68
Relative Nutrient Element Uptake (% of Maximum) of Oats in Relation to Plant Development

Growth Stage	Dry Matter	Nitrogen	Phosphorus as Phosphate	Potassium as Potash
Early growth	0	0	0	0
Tillering	1	16	10	11
Jointing	1	31	14	19
Booting	3	34	20	31
Ear emergence	5	68	60	88
Flowering	7	85	74	100
Grain formation	10	97	100	98
Physiological Maturity				
Biomass (dry)	90	100	100	94
Grain	5	74	64	18

Source: *IFA World Fertilizer Use Manual*, 2000, International Fertilizer Industry Association, Paris.

TABLE 2.69
Nutrient Element Utilization (lb/acre) by 100-bu/acre Oat Crop

Nutrient Element				
Nitrogen	Phosphorus as Phosphate	Potassium as Potash	Magnesium	Sulfur
115	40	145	20	19

TABLE 2.70
Nutrient Element Sufficiency Ranges for Oats

Major Elements	%	Micronutrients	ppm
Nitrogen	2.00–3.00	Copper	5–25
Phosphorus	0.20–0.50	Iron	40–150
Potassium	1.50–3.00	Manganese	25–100
Calcium	0.20–0.50	Molybdenum	0.20–0.30
Magnesium	0.15–0.50	Zinc	15–70
Sulfur	0.15–0.40		

Note: Sampling procedure: 25 whole tops as head emerges from boot.

Source: Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide, 1996, MicroMacro Publishing, Athens, GA.

2.4.4 Nutrient Element Deficiencies[1]

2.4.4.1 Boron (B)

2.4.4.1.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Boron-deficient plants are stunted and have dull yellow-green foliage. Although tiller production is usually not affected, many tiers die before maturity if a deficiency persists. Whole plants may die before producing heads if a deficiency is very severe. As a result, both forage and grain yields are reduced.

Chlorotic tips on younger leaves: Boron is immobile in plants and symptoms develop first and are more severe on young leaves. Old leaves remain dark green. They appear healthy, but may turn a dull orange-green when a deficiency is severe. Marginal, dull yellow chlorosis develops at the tips of young leaves. The remainders of the leaves turn dull green-yellow. As the symptoms develop, leaf tips turn dull orange-green and pale brown necrotic lesions appear between the mid-veins and margins in the upper halves of the leaves. The chlorotic leaf tips die and turn pale orange-brown.

Fan-shaped stems: Because B plays a major role in the elongation of stems and leaves, stems of deficient plants are very short and stout. The leaves are often crowded at the tops of the stems, forcing the leaf sheaths apart so the stems appear fan-shaped.

2.4.4.1.2 Problem Soils

Boron deficiency is likely to occur in:

- Soils derived from parent material low in B, such as acid igneous rocks or freshwater sediments
- Sandy soils from which B has been leached
- Calcareous soils, especially those containing free lime
- Soils low in organic matter
- Acid peat and muck soils

2.4.4.1.3 Correcting Deficiency

Boron deficiency can be corrected by applying soil dressings or foliar sprays of B fertilizers. Soil dressings are more effective if broadcast and mixed into the soil some months before sowing. Borax, boric acid, and chelated B compounds are suitable for soil application, but only boric acid and chelated B are suitable for foliar sprays because of the low solubility of borax. Sprays should be applied within the first 5 weeks of seedling emergence or as soon as foliar symptoms appear. While foliar sprays are often beneficial, they have little residual value. Soil dressings can remain effective for many years.

Soil tests can estimate the amount of available B and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

2.4.4.2 Calcium (Ca)

2.4.4.2.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Calcium-deficient oat plants are very stunted and have short, dark green foliage. Tillering is not affected if the deficiency is mild. If it persists, many tillers die before producing heads. Forage and grain production are much reduced and, in some instances, whole plants die when the deficiency is severe.

Weather-tipped younger leaves: The symptoms begin and are more severe on young leaves because Ca is not readily transferred from old to young leaves when a deficiency occurs. Old leaves usually remain dark green and appear healthy. Young leaves cease growth and become erect, short, and pale green. The leaf tips wilt and hang down, often with the margins rolled inward into tubes.

Eventually the leaf tips die and turn grey (weather-tipped), sometimes breaking off to produce squared ends.

Ragged leaf margins on younger leaves: When a deficiency is very severe, the youngest leaves become brittle and are easily torn as they emerge. Hence, the margins of young leaves often appear ragged.

Death of shoots: As the deficiency persists, growing points of shoots die. The youngest leaves may die before emerging fully from the sheaths of previous leaves.

2.4.4.2.2 Problem Soils

Calcium deficiency is likely to occur in:

- Acid sandy soils from which Ca has been removed by heavy rainfall
- Strongly acid peat and muck soils whose total Ca is low
- Alkaline or sodic soils in which high exchangeable Na and pH inhibit Ca uptake
- Soils with high levels of soluble Al and low levels of exchangeable Ca

2.4.4.2.2 Correcting Deficiency

Calcium deficiency can be corrected by broadcasting a suitable fertilizer onto the soil some months before sowing. Subsequent tillage operations will thoroughly mix the fertilizer and soil. Where the chief problem is a lack of Ca, suitable fertilizers are gypsum (calcium sulfate) and calcium nitrate or chloride. However, if the soil pH is low, lime or limestone (calcium carbonate) and dolomite (a mixture of calcium and magnesium carbonates) are more suitable.

A soil test can be used to determine lime or Ca requirements. However, since the correct rate of application depends on the soil type and the crop to be grown, advice should be sought on fertilizer practices used on similar soils in the district. The excessive use of lime may induce deficiencies of K, Mg, Fe, Mn, Zn, and Cu, and care should be taken to prevent over-liming.

2.4.4.3 Copper (Cu)

2.4.4.3.1 Deficiency Symptoms

Patchy, low-yielding crops: Even in mild deficiencies, affected crops often have a patchy appearance. Within Cu-poor areas, plants are stunted and pale green and appear limp or wilted. If the deficiency is severe, young leaves may be dead while old leaves remain green. If the deficiency is mild, tiller production is usually unaffected and additional late tillers may develop at nodes or joints above ground level. However, severe deficiency causes many tillers to die before maturing. Because Cu deficiency leads to production of sterile pollen, heads on apparently healthy plants may set few grains and yields are reduced. When easily recognizable symptoms are present, little or no grain may be set.

Weather-tipped younger leaves: Because Cu is immobile in plants, the symptoms develop first and are more severe on young leaves. Old leaves remain green and apparently healthy. The symptoms begin when young leaves turn pale green and appear to wilt even when ample water is available. If the deficiency persists, the tips of young leaves develop pale yellow chlorosis, then die and turn dark brown (weather-tipped). The dead tissue usually rolls or twists tightly into tubes or spirals.

2.4.4.3.2 Problem Soils

Copper deficiency is likely to occur in:

- Peat and muck soils in which organic matter ties up Cu in forms unavailable to plants
- Calcareous sands whose total Cu is low
- Leached acid soils whose total Cu is low
- Soils formed from rocks low in Cu

2.4.4.3.3 Correcting Deficiency

Foliar sprays and soil dressings of salts such as copper sulfate (bluestone) or copper chelates have corrected deficiencies. Soil dressings should be broadcast and mixed into the soil some months before planting. However, such dressings sometimes fail to correct the deficiencies or symptoms reappear. If this occurs, foliar sprays should be applied immediately.

A reliable remedy is to apply two or three foliar sprays (for example, 0.5 to 1 kg copper sulfate per 100 L water per ha). The first spray should be applied 5 to 6 weeks after seedlings emerge and the second when the first or oldest heads reach the boot stage. An optional third spray may be applied 7 to 10 days after the second spray.

Tests can estimate the amount of available Cu in the soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

2.4.4.4 Iron (Fe)

2.4.4.4.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Iron deficiency causes stunted growth and pale green to yellow foliage. If the deficiency is mild, tillering may be relatively unaffected. In severely deficient plants it is very reduced, and forage and grain yields are greatly reduced.

Interveinal yellow chlorosis on younger leaves: Iron is not easily transferred from old to young leaves when a deficiency occurs. Hence, symptoms begin and are more severe on young leaves, often on leaves that have not fully unrolled. Old leaves usually remain dark green and appear healthy. The symptoms begin when young leaves turn pale green. As the deficiency becomes more severe, the interveinal areas of affected leaves become bright yellow while the veins remain green and stand out prominently. If the deficiency persists, the interveinal areas may turn white and the veins become pale green to yellow.

2.4.4.4.2 Problem Soils

Iron deficiency is likely to occur in:

- Calcareous soils whose levels of soluble Fe are low
- Waterlogged soils
- Acid soils excessively high in soluble Mn, Zn, Cu, and Ni that inhibit Fe uptake
- Sandy soils low in total Fe
- Peat and muck soils in which organic matter ties up Fe

2.4.4.4.3 Correcting Deficiency

While soil dressings of inorganic iron salts such as iron sulfates or chlorides correct deficiencies in some soils, it appears that applied Fe quickly becomes insoluble and less available. Iron salts of various organic chelates appear more promising because the chelate form keeps the Fe in solution. For acid soils, FeEDTA is the most effective chelate, while FeHEDTA and FeDTPA are best on neutral soils and FeEPDHA is best for calcareous soils. However, large amounts of chelates may be required and may prove too costly.

An equally effective remedy is applying solutions of inorganic salts or chelates to the foliage (1% solution or 1 kg salt per 100 L water per ha). Because Fe is so immobile in plants, the sprays may need to be applied every 10 to 15 days to provide Fe to new leaves. Advice on local fertilizer practices should be sought.

2.4.4.5 Magnesium (Mg)

2.4.4.5.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Magnesium deficiency causes stunted plants with pale green foliage that often turns orange-purple. Tillering can be greatly reduced when the deficiency appears in young plants. If the deficiency persists or becomes severe, young tillers die before producing heads and mature tillers develop small heads. Yields of forage and grain are reduced.

Interveinal chlorosis on older leaves: Because Mg is easily transferred from old to young leaves when a deficiency occurs, symptoms begin and are more severe on old leaves, working up the plant to young leaves if it persists. The youngest leaves usually remain green to pale green and appear healthy. On very young plants, old leaves turn pale green and develop yellow chlorosis near the margins around the middles of the leaves. On more mature plants, linear yellow or white lesions develop in interveinal tissue in the mid-sections. The chlorosis and lesions advance toward the tips and bases of the leaves, developing into yellow or yellow-red, interveinal chlorosis. If the deficiency is severe, affected leaves develop generalized orange-red chlorosis, die, and turn pale brown.

2.4.4.5.2 Problem Soils

Magnesium deficiency is likely to occur in:

- Acid sandy soils from which Mg has been removed by leaching
- Strongly acid peat and muck soils whose total Mg is low
- Soils that have been over-fertilized with Ca (for example, lime) or K, thus inhibiting Mg uptake

2.4.4.5.3 Correcting Deficiency

Magnesium deficiency on acid soils is corrected by broadcasting dolomite (a mixture of calcium and magnesium carbonates) onto the surface some months before sowing and mixing it thoroughly throughout the topsoil. When the problem is strictly Mg deficiency, band applications of magnesium sulfate or chloride can be made at or before planting. A test can estimate the amount of soluble and exchangeable Mg in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Magnesium deficiency in existing crops can be corrected by applying soluble salts such as magnesium sulfate, chloride, or nitrate with irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to meet crop requirements.

2.4.4.6 Manganese (Mn)

2.4.4.6.1 Deficiency Symptoms

Patchy, low-yielding crops: Magnesium deficiency may cause areas of poor growth and give a crop a patchy appearance. Within Mn-poor areas, plants are stunted and have short, stout stems and pale green to brown foliage. If the deficiency becomes severe or persists, plants in these areas may die. Deficient plants produce few tillers and many die. As a result, both forage and grain yields are reduced.

Grey flecks in older leaves: Because Mn is partly mobile in oats, the symptoms first appear and become more severe on mature leaves about halfway up the shoots. If the deficiency persists, symptoms spread rapidly to older leaves, then up the shoots to younger leaves until whole plants are affected. Small, linear, grey flecks appear in interveinal tissues in the basal halves of old leaves, extending toward the tips as symptoms develop. The flecks join to form large grey lesions in the basal halves of the leaves between the margins and mid-veins, eventually affecting the veins and causing the leaves to collapse. The necrotic areas finally turn pale brown.

2.4.4.6.2 Problem Soils

Manganese deficiency is likely to occur in:

- Calcareous soils in which Mn is less available to plants
- Poorly drained peaty soils
- Strongly acid sandy soils whose soluble Mn has been leached by heavy rain
- Soils formed from rocks low in Mn

2.4.4.6.3 Correcting Deficiency

Foliar sprays and soil dressings of Mn salts and oxides have been used to correct deficiencies. Soil dressings are more effective when broadcast and mixed into the soil some months before sowing. However, foliar sprays have generally been more successful. One or more foliar sprays of 0.5 to 1% solutions of manganese sulfate (0.5 to 1 kg manganese sulfate per 100 L water per ha) usually correct the deficiency, the first spray to be applied 5 to 6 weeks after seedling emergence. If symptoms reappear, the spray should be repeated immediately.

Tests can estimate the amount of available Mn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

2.4.4.7 Nitrogen (N)

2.4.4.7.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Nitrogen-deficient oats lack vigor and yield poorly. In young crops, stems are short and thin and the foliage is pale green. Mature plants are stunted and appear multicolored. Upper leaves are pale green, short, and erect. Middle leaves are usually yellow to pale green with red tips. The oldest leaves may be dead and brown and lie in the soil around the bases of the plants. Even mild deficiency reduces the number of tillers produced. When a deficiency persists, many young tillers die before producing heads. As a result, forage and grain yields are reduced. Furthermore, the protein concentration is low because of the central role N plays in protein formation.

Pale yellow older leaves: When a deficiency occurs, N is transferred from old to young leaves. Symptoms appear first on old leaves and work up the plant to younger leaves if the deficiency persists. Old leaves turn pale green. Pale yellow chlorosis develops at the tips and advances toward the bases until entire leaves are pale yellow.

Red leaf tips: When a deficiency persists or becomes severe, the tips of the leaves become orange-red. As the tissue dies, it turns dark brown and the leaf margins often roll upward to form tubes.

Red stems: Stems are thin and spindly. Leaf sheaths are usually pale green but red striping often develops in cold weather.

2.4.4.7.2 Problem Soils

Nitrogen deficiency is likely to occur in:

- Sandy soils leached by heavy rainfall or excessive irrigation
- Soils low in organic matter
- Soils with a long history of cropping where N stores have been used up

Even fertile soils may suffer temporary N deficiencies when double-cropped, heavily leached, or waterlogged.

2.4.4.7.3 Correcting Deficiency

Nitrogen deficiency is corrected by increasing the level of available N in the soil by fallowing, to allow organic N to be converted to mineral N; by growing cover or cash crops of legumes, which can fix atmospheric N_2; or by adding nitrogenous fertilizers such as urea, gaseous ammonia, or ammonium sulfate, nitrate or phosphates. Crop growth depends on the amount of N already in the soil.

A soil test can measure the amount of total N or nitrate-N in soil and predict the amount of fertilizer required. The best prediction is obtained by seeking advice on fertilizer practices used on similar soils in the district. Nitrogen deficiency in existing crops can be corrected by applying soluble salts such as urea as solids or with irrigation water.

2.4.4.8 Phosphorus (P)

2.4.4.8.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Phosphorus-deficient crops are unthrifty and yield poorly. Affected plants are stunted and have erect, short, dark green leaves with bright red-purple tips. In severe deficiencies, the oldest leaves may be brown and dead and lie on the soil around the bases of the plants. Tiller production is reduced and the youngest tillers usually die before maturity. As a result, yields of both foliage and grain are severely depressed.

Dark yellow-orange chlorosis on older leaves: Phosphorus deficiency symptoms are more severe on old leaves, working up the plants to younger leaves if the deficiency persists because P is transferred from old to young leaves when a deficiency occurs. Dark orange-yellow chlorosis begins at the tips of affected leaves and advances toward the bases, usually along the leaf margins.

Red or purple tips on older leaves: If the deficiency persists or becomes severe, chlorotic tissue dies and turns red or purple. Affected leaves often have green bases, orange-yellow mid-sections, and bright red or purple tips. The margins of the leaf tips often roll inward to form tubes. Eventually, entire leaves die and turn dark brown.

Purple stems: The leaf sheaths and stems of affected plants often turn purple, especially if the season is cold.

2.4.4.8.2 Problem Soils

Phosphorus deficiency is likely to occur in:

- Soils low in organic matter
- Soils in which cropping has exhausted the stores of P
- Highly weathered, Fe-rich acid soils in which phosphate is fixed in unavailable forms
- Soils whose topsoil has been lost through erosion
- Calcareous soils in which much of the P is tied up in insoluble phosphates that are less available to plants

2.4.4.8.3 Correcting Deficiency

Phosphorus deficiency can be corrected by applying phosphatic fertilizers to the soil at or before sowing. Suitable fertilizers are single or triple superphosphates or ammonium phosphates. The growth of crops depends on the amount of available water-soluble phosphate and the rate of exchange between insoluble and soluble forms of P in the soil. Tests can estimate the amount of available P in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices in the district.

Phosphorus deficiency in existing crops can be corrected by applying soluble salts such as ammonium phosphates with irrigation water. Spray applications of similar salts are usually not recommended because of the large number needed to satisfy crop requirements.

2.4.4.9 Potassium (K)

2.4.4.9.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Potassium-deficient oat plants are stunted and exhibit sprawling growth. Foliage is green with brownish-yellow lesions. Stems are short and stout and leaf sheaths often develop brownish lesions similar to those on the leaf laminae. As affected leaves die, plants develop a three-tone appearance. Younger leaves are green, middle leaves are green with yellow to bronze areas, and older leaves are brown and dead. Tiller production may be unaffected but when a deficiency persists, many tiers die before maturity. Because of the severe stunting and deaths of tillers, K deficiency greatly reduces forage and grain yields.

Bronze-yellow older leaves: Because K is readily transferred from old to young leaves when a deficiency occurs, symptoms appear first and are more severe on old leaves, working up the plant to younger leaves if it persists. Affected leaves turn pale green and develop bronze-yellow chlorosis in their mid-sections between the margins and mid-veins. The chlorosis rapidly extends toward the tips until two thirds of the leaves turn bronze-yellow. In some varieties, the chlorosis may be orange-red.

Necrotic lesions on older leaves: Grey-brown necrotic lesions develop in the chlorotic tissues of old leaves, usually beginning in the mid-sections between the mid-veins and margins. Eventually the lesions join and affect the mid-veins, causing the leaves to bend downward. Similar lesions develop on the sheaths of old leaves. Affected leaves die, turn brown, and form thatches of dead leaves at the plant bases.

2.4.4.9.2 Problem Soils

Potassium deficiency is likely to occur in:

- Soils whose organic matter was depleted by many years of cropping, and particularly where hay was cut
- Sandy soils formed from parent material low in K
- Light textured soils whose K has been leached by rainfall

2.4.4.9.3 Correcting Deficiency

Potassium deficiency is corrected by applying potassium nitrate, sulfate, or chloride to the soil at or before sowing. Yield depends on the amount of water-soluble and exchangeable K in the soil.

Tests can estimate the amount of available K in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district. Potassium deficiency in existing crops can be corrected by applying soluble salts such as potassium sulfate, chloride, or nitrate with irrigation water. The foliar application of similar salts is usually not recommended because of the large number of sprays required.

2.4.4.10 Sulfur (S)

2.4.4.10.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Sulfur deficiency leads to stunted plants with yellow to pale green foliage. In young crops, the whole plant is often pale green. In more mature crops, young leaves are pale green to yellow, giving the field a distinct yellow appearance. Tiller production is severely reduced and heads are smaller than normal. As a result, both forage and grain yields are depressed. Forage and grain from affected plants are usually low in protein because S deficiency depresses the conversion of N into protein.

Yellow or white younger leaves: Because S is not readily transferred from old to young leaves when a deficiency occurs, the first and more severe symptoms occur on younger leaves. Symptoms begin with the youngest leaves turning pale green, then pale yellow. The chlorosis is not confined

to the interveinal areas. Entire leaves take on the same color. Necrosis (death) of tissues is rare even when leaves turn pale yellow. Old leaves usually remain dark green but may become pale green if the deficiency persists or becomes severe. When a deficiency is very severe, old leaves may develop orange-red margins.

Purple streaked stems: Stems are short and thin. Leaf sheaths are usually pale green, but purple streaks often develop when a deficiency is very severe.

2.4.4.10.2 Problem Soils

Sulfur deficiency is likely to occur in:

- Soils whose organic matter has been depleted by many years of cropping
- Soils formed from parent material low in S (for example, some volcanic rocks and ash)
- Acid sandy soils whose sulfates have been leached

2.4.4.10.3 Correcting Deficiency

Soil dressings of any S fertilizer will correct deficiencies. Elemental S (flowers of sulfur) may be broadcast onto the soil and thoroughly mixed in, about 4 months before sowing. Gypsum (calcium sulfate) is another useful source of S.

Tests can estimate the amount of available sulfate in a soil before sowing and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Sulfur deficiency in existing crops can be corrected by applying soluble sulfate salts such as magnesium, ammonium, or potassium sulfate in irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed.

2.4.4.11 Zinc (Zn)

2.4.4.11.1 Deficiency Symptoms

Patchy, low-yielding crops: Zinc deficiency often causes patchy growth. In Zn-poor areas, plants are stunted and have pale green foliage and yellow or orange-red leaf tips. Tiller production may not be affected, but if a deficiency is severe or persists, many tillers die before producing heads. As a result, forage and grain yields can be reduced greatly.

Yellow, orange, purple, or black tips on older leaves: Zinc is only partly mobile in oats and symptoms appear first and are more severe on middle and old leaves, working up the plant to younger leaves if deficiency persists. The youngest leaves usually remain green and appear healthy. Initially, middle and older leaves turn pale green and develop pale yellow chlorosis between the margins and mid-veins at the tips. As the deficiency progresses, the chlorosis becomes more extensive and general, turning dark yellow, orange-red, or purple. Brown necrotic lesions appear in the chlorotic tissues and increase in size until the leaf tips die, often turning red-brown to black. Frequently, the basal portions of leaves remain green while the mid-sections are chlorotic and the leaf tips turn dark brown or black.

Crowded leaves: When a deficiency is very severe, stems are short and the youngest leaves sometimes have difficulty emerging fully from the sheaths of older leaves. This leads to the crowding of leaves on top of the short stems.

2.4.4.11.2 Problem Soils

Zinc deficiency is likely to occur in:

- Calcareous soils in which the availability of Zn is depressed
- Leached sandy soils whose total Zn is low
- Leveled soils in which Zn-deficient subsoils may be exposed on the surface
- Soils in which heavy, frequent applications of phosphate fertilizers may have reduced Zn uptake

21.4.4.11.3 Correcting Deficiency

Foliage and soil applications of Zn salts have been used to correct deficiencies. Soil dressings of zinc chelates, sulfates, or oxides should be broadcast and mixed into the soil 2 to 3 months before sowing. While soil applications have residual effects lasting 6 to 8 years, foliar sprays have no residual effects and fresh applications must be made to each crop. Best results are obtained when two sprays of a 0.5 to 1% solution of zinc sulfate heptahydrate (0.5 to 1 kg zinc salt per 100 L water per ha) are applied about 2 weeks apart, the first sprayed 2 to 3 weeks after seedling emergence.

Tests can estimate the amount of available Zn in the soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

2.4.4.12 Manganese Toxicity[1]

2.4.4.12.1 Toxicity Symptoms

Unthrifty, low-yielding crops: Manganese toxicity causes stunted plants to produce stout stems and dull green foliage. If the toxicity becomes severe or persists, the leaves develop bronze-orange areas. Tiller production is usually not affected initially, but some may die if the toxicity persists. Mature tillers often produce small heads. As a result, forage and grain yields can be greatly reduced.

Dull-colored leaves: Excess Mn accumulates in old leaves. Hence symptoms appear first and are more severe on old leaves, working up the plant to younger leaves if the toxicity persists. All leaves present a dull appearance, ranging from dull green in young leaves to dull bronze-green in old leaves. If the toxicity persists, entire plants appear dull bronze-green.

Chlorosis on older leaves: Bronze-orange chlorosis develops on old leaves between the margins and the mid-veins near the points of attachment of the laminae and leaf sheaths. The chlorosis advances up the leaves between the margins and mid-veins, eventually affecting whole leaves. As the concentration of Mn becomes toxic, affected tissues die and turn brown.

Broken leaves: When the toxicity is severe, the mid-veins die near the points of attachment of the laminae and leaf sheaths, thus weakening the leaves and allowing the laminae to bend down and lie on the soil.

2.4.4.12.2 Problem Soils

Manganese toxicity is likely to occur in:

- Strongly acid soils that have increased solubility of Mn
- Waterlogged soils in which poor aeration causes unavailable manganic (Mn^{3+}) ions to reduce to manganous (Mn^{2+}) ions that can be taken up by plants

2.4.4.12.3 Correcting Toxicity

Manganese toxicity is usually corrected by adopting management practices that reduce the level of soluble Mn in the soil. Liming of strongly acid soils and drainage of waterlogged soils are effective measures. If soils have been over-fertilized with Mn, heavy leaching with low Mn irrigation water or mulching with organic materials removes soluble Mn from the root zones of plants. Acid-reacting fertilizers should not be used on acid soils high in Mn. Care should be taken also when applying Mn fertilizers to prevent over-fertilization.

2.4.4.13 Salinity[1]

2.4.4.13.1 Salinity Symptoms

Unthrifty, low-yielding crops: When sodium chloride (NaCl) levels in soils or irrigation water become excessive, oat plants become stunted and develop harsh, droughty appearance. The foliage

turns dull, bluish yellow-green. While tillering may not be affected initially, many tillers die if the toxicity persists. Yields of both forage and grain are reduced.

Wilted appearance: High levels of NaCl in soil make it difficult for plants to take up water. Hence, they develop a harsh, droughty appearance even when ample water is available. They often wilt on hot days and recover overnight.

Dull-colored leaves: Sodium chloride is carried in the transpiration stream to the margins and tips of leaves. Because older leaves had more time to accumulate NaCl, their symptoms are more severe. The foliage has a dull appearance, ranging from dull green in young leaves to dull, bluish yellow-green in old leaves. If the toxicity persists, the whole plant develops a bluish-green color.

Yellow tips on older leaves: As NaCl accumulates in the leaf tips, it eventually reaches concentrations that kill tissues. Dull yellow chlorosis develops on the tips of old leaves, followed by yellow-grey necrosis when the tissues die. The chlorosis and necrosis advance down the margins until entire leaves are dead.

2.4.4.13.2 Problem Soils

Sodium chloride toxicity is more likely to occur in:

- Saline soils formed from salt water sediments
- Previously fertile soils flooded or heavily irrigated with water containing high concentrations of NaCl

2.4.4.13.3 Correcting Toxicity

Leaching with good quality irrigation water is the most effective means of removing excess Na or Cl from the soil. The water table may have to be lowered. Permeable soils such as well structured sandy soils are often easily reclaimed, but the problem is more difficult in less permeable soils (for example, poorly structured heavy clays).

If exchangeable Na in the soil is high, reclamation involves replacement of the adsorbed Na with Ca by applying gypsum (calcium sulfate) and then leaching the dissolved Na and Cl beyond the rooting depths of the plants. If irrigation water is to be used to leach the Na, its quality should be checked before use to make sure it is not saline. Where excess NaCl cannot be wholly corrected by soil leaching, a more tolerant species may have to be grown.

2.4.5 Weights and Measures

The net weight of 1 bu of oat grain is approximately 32 lb or 14.5 kg.

TABLE 2.71
Crop Seeds/Pound, Weight/Bushel, and Germination Time

Seeds/lb (1,000)	Seeds/g (number)	Weight/bu	Germination Time (days)
14	30	32	10

REFERENCES

1. Grundon, N.J., *Hungry Crops: A Guide to Nutrient Deficiencies in Field Crops*, 1987, Queensland Department of Primary Industries, Brisbane, Australia.

2.5 RICE (*Oryza sativa* L.)

2.5.1 Introduction

Rice belongs to the Gramineae grass family. It is known as riz in France, arroz in Spain, riso in Italy, and reirs in Germany. It is a vital food crop because half the world's population eats rice as a main part of their diets. Rice ranks second only to wheat in terms of area harvested. It provides more calories per hectare than any other cereal grain. Most people who depend heavily on rice live in Asia. Asian farmers grow about 90% of the world's rice. It grows during the wet season that starts in June or July. Rice grows best in warm temperatures with plentiful moisture from rainfall or irrigation, and is most frequently grown in valley and river deltas. It grows in more than 100 countries. Crops cover about 360 million acres and production is about 580 million short tons.

The three Asian rice groups are *Indica,* grown in India and other tropical regions; *Japonica,* cultivated in cooler Asian regions (China, Japan, and Korea), Europe, North America, and Australia; and *Javanica,* grown in Indonesia. Rice is also classified by the method of culture. *Lowland rice* is grown in flat fields that are flooded by irrigation and in enclosed fields called *paddies. Upland rice* depends on rainfall for moisture and accounts for only 6% of all rice grown. Highest grain yields for irrigated rice range from 7 to 10 tons per ha in dry seasons when well irrigated and 5 to 8 tons per ha in wet seasons. Rain-fed rice yields an average of 1 ton per ha. Each ripened rice panicle contains 80 to 120 grains.

Evidence indicates that rice was cultivated about 5,000 B.C. in southern China and northern Thailand, Laos, and Vietnam. Cultivation later spread to northern China, Japan, and Korea, west to India, and south to Indonesia. Rice reached the American Colonies during the 1600s, and was grown commercially in South Carolina as early as 1685. Rice production moved west. By 1900, about 70% of the rice grown in the U.S. was from Louisiana. It became an established crop in California around the same time.

In the 1960s, the worldwide *Green Revolution* brought, through plant breeding and production trials, higher yielding varieties that had shorter, sturdier stems and responded to fertilization. The International Rice Institute, established in 1960 and located in the Philippines, is devoted to improving cultivation. It conducts research and provides extension services in an effort to increase food production throughout the developing world.

2.5.2 Classification and Terminology

2.5.2.1 Classes

Classes are based mainly on type of rice. All class designations are explained in the *Definitions* section. The four main classes of rice are:

1. Long-grain rice
2. Medium-grain rice
3. Short-grain rice
4. Mixed rice

The following additional classes apply only to milled rice and are based on the percentages of whole kernels and broken kernels of different sizes they contain:

1. Second head milled rice
2. Screenings milled rice
3. Brewers milled rice

2.5.2.2 Types

Rice types are based on the length:width ratios of unbroken kernels of rice and the widths, thicknesses, and shapes of broken kernels, as set forth in the *Rice Inspection Handbook*.[1] All type designations are explained in the *Definitions* section. The types are:

1. Long grain
2. Medium grain
3. Short grain

2.5.2.3 Special Grades

A special grade designation is supplemental to the grade assigned and includes the following terms: *coated*, *granulated*, *parboiled*, *parboiled light*, *parboiled dark*, and/or *undermilled*.[2] Special grades for milled rice are:

Coated milled rice
Granulated brewers milled rice
Parboiled milled rice
Undermilled milled rice

2.5.2.4 Definitions[2]

Brewers milled rice Milled rice containing not more than 25% whole kernels and that does not meet the kernel size requirements of the second head milled rice or screenings milled rice class.

Brown rice for processing Rice consisting of more than 50% kernels of brown rice and is intended for processing to milled rice.

Coated milled rice Special grade of rice that is coated in whole or in part with safe and suitable substances according to commercially accepted practice.

Damaged kernels Whole or large broken kernels that are distinctly discolored or damaged by water, insects, heat, or other means, and whole or large broken kernels of parboiled rice in nonparboiled rice. Heat-damaged kernels (see below) shall not function as damaged kernels.

Granulated brewers milled rice Special grade of milled rice that is crushed or granulated so that 95% or more will pass through a 5 sieve, 70% or more will pass through a 4 sieve, and not more than 15% will pass through a 2 1/2 sieve.

Heat-damaged kernels Whole or large broken kernels of rice that are materially discolored and damaged as a result of heating, and whole or large broken kernels of parboiled rice in nonparboiled rice that are as dark as or darker than the interpretive line for heat-damaged kernels.

Long-grain brown rice for processing Brown rice for processing that contains more than 25% whole kernels of brown rice and not more than 10% whole or broken kernels of medium- or short-grain rice.

Long-grain milled rice Milled rice that contains more than 25% whole kernels of milled rice; in U.S. Nos. 1 through 4, not more than 10% whole or broken kernels of medium- or short-grain rice. U.S. Nos. 5 and 6 long-grain milled rice shall contain not more than 10% whole kernels of medium- or short-grain milled rice. Broken kernels do not apply.

Long-grain rough rice Rough rice that contains more than 25% whole kernels and after milling to a well-milled degree, contains not more than 10% whole or large broken kernels of medium- or short-grain rice.

Medium-grain brown rice for processing Brown rice for processing that contains more than 25% whole kernels of brown rice and not more than 10% whole or broken kernels of long-grain or short-grain rice.

Medium-grain milled rice Milled rice that contains more than 25% whole kernels of milled rice; in U.S. Nos. 1 through 4, not more than 10% whole or broken kernels of long-grain rice or whole kernels of short-grain rice. U.S. Nos. 5 and 6 medium-grain milled rice shall contain not more than 10% whole kernels of long- or short-grain milled rice. Broken kernels do not apply.

Medium-grain rough rice Rough rice that contains more than 25% whole kernels and after milling to a well-milled degree, contains not more than 10% whole or large broken kernels of long-grain rice or whole kernels of short-grain rice.

Milled rice Whole or broken kernels from which the hulls or at least the outer bran layers have been removed; contains not more than 10% seeds, paddy kernels, or foreign material, either singly or combined.

Milling yield Estimate of the quantity of whole kernels and total milled rice (whole and broken kernels combined) produced in the milling of rough rice to a well-milled degree.

Mixed brown rice for processing Brown rice for processing that contains more than 25% whole kernels of brown rice and more than 10% other types (see below).

Mixed milled rice Milled rice that contains more than 25% whole kernels of milled rice and more than 10% other types. U.S. Nos. 5 and 6 mixed milled rice shall contain more than 10% whole kernels of other types. Broken kernels do not apply.

Mixed rough rice Rough rice that contains more than 25% whole kernels; after milling to a well-milled degree, contains more than 10% other types (see below).

Objectionable seeds Seeds other than rice, except seeds of *Echinochloa crusgalli* (commonly known as barnyard grass, water grass, and Japanese millet).

Other types (A) Whole kernels of (i) long grain rice in medium- or short-grain rice, (ii) medium-grain rice in long- or short-grain rice, (iii) short-grain rice in long- or medium-grain rice; (B) large broken kernels of long grain rice in medium- or short-grain rice and large broken kernels of medium- or short-grain rice in long-grain rice. Large broken kernels of medium-grain rice in short-grain rice and large broken kernels of short-grain rice in medium-grain rice shall not be considered other types.

Paddy kernels Whole or broken unhulled kernels.

Parboiled milled rice Special grade of milled rice in which the starch has been gelatinized by soaking, steaming, and drying. U.S. Nos. 1 through 6 shall contain not more than 10% ungelatinized kernels. U.S. Nos. 1 and 2 shall contain not more than 0.1%. U.S. Nos. 3 and 4 shall contain not more than 0.2%. U.S. Nos. 5 and 6 shall contain not more than 0.5% nonparboiled rice. If the rice is (A) not distinctly colored by parboiling, it shall be considered parboiled light; (B) distinctly but not materially colored by parboiling, it shall be considered parboiled; (3) materially colored by parboiling, it shall be considered parboiled dark. Color levels for parboiled light, parboiled, and parboiled dark shall be in accordance with interpretive line samples for parboiled rice. The maximum limits for chalky kernels, heat-damaged kernels, kernels damaged by heat, and color requirements are not applicable to the parboiled milled special grade.

Red rice Whole or large broken kernels that contain appreciable amounts of red bran.

Rough rice Consists of 50% or more paddy kernels.

Screenings milled rice Milled rice that contains (A) not more than (i) 25% whole kernels, (ii) 10% broken kernels removed by a 5 plate, and (iii) 0.2% broken kernels passing through a 4 sieve (southern production); or (B) not more than (i) 25% whole kernels, (ii) 15% broken kernels passing through a 5 1/2 sieve, (iii) more than 50% broken kernels passing through a 6 1/2 sieve, and (iv) 10% broken kernels passing through a 6 sieve (western production).

Second head milled rice Milled rice that contains (A) not more than (i) 25% whole kernels, (ii) 7% broken kernels removed by a 6 plate, (iii) 0.4% broken kernels removed by a 5 plate, and (iv) 0.05% broken kernels passing through a 4 sieve (southern production); or (B) not more than (i) 25% whole kernels, (ii) 50% broken kernels passing through a 6 1/2 sieve, and (iii) 10% broken kernels.

Seeds Whole or broken seeds of any plant other than rice.

Short-grain brown rice for processing Brown rice for processing that contains more than 25% whole kernels of brown rice and not more than 10% whole or broken kernels of long-grain rice or whole kernels of medium-grain rice.

Short-grain milled rice Milled rice that contains more than 25% whole kernels of milled rice; in U.S. Nos. 1 through 4, not more than 10% whole or broken kernels of long-grain rice or whole kernels of medium-grain rice. U.S. Nos. 5 and 6 short-grain milled rice shall contain not more than 10% whole kernels of long- or medium-grain milled rice. Broken kernels do not apply.

Short-grain rough rice Rough rice that contains more than 25% whole kernels; after milling to a well-milled degree, contains not more than 10% whole or large broken kernels of long-grain rice or whole kernels of medium-grain rice.

Smutty kernels Whole or broken kernels of rice that are distinctly infected by smut.

Undermilled milled rice Special grade of milled rice that does not meet the requirements for well milled, reasonably well milled, or lightly milled rice, U.S. Nos. 1 and 2 shall contain not more than 5%, U.S. Nos. 3 and 4 shall contain not more than 5%, U.S. No. 5 shall contain not more than 10%, and U.S. No. 6 shall contain not more than 15% well milled kernels. U.S. No. 5 shall contain not more than 10% red rice and damaged kernels (singly or combined), and in no case, more than 6% damaged kernels. Color and milling requirements are not applicable to the undermilled milled rice special grade.

Ungelatinized kernels Whole or large broken kernels of parboiled rice with distinct white or chalky areas resulting from incomplete gelatinization of starch.

Whole kernels Unbroken kernels of rice that comprise at least 3/4 of an unbroken kernel.

Whole and large broken kernels Rice (including seeds) that (A) passes over a 6 plate (southern production) or (B) remains on top of a 6 sieve (western production).

2.5.2.5 Glossary[2]

Adventitious Plant structure arising from an unusual place.

Anaerobic Without oxygen.

Auricle Narrow extension of the collar in grasses; may completely clasp the culm; may be absent.

Blank Individual floret of rice that produces no grain.

Boot Growth stage identified by the bulge within the flag leaf sheath caused by the enlarging panicle.

Borrow pit Depression on each side of a rice levee created when soil is embanked.

Brewers Smallest size of broken milled rice, less than 1/4 of a whole kernel.

Broken Milled rice containing less than 3/4 whole kernels; includes second heads, screenings, and brewers.

Broken yield Broken grain resulting from milling 100 lb of rough rice; equals total mill yield minus head yield.

Brown rice Rice with the hull removed; bran and embryo remain.

Carbohydrate Organic chemical composed of carbon (C), hydrogen (H), and oxygen (O); photosynthetically produced sugar and starch found in plants.

Chlorosis Yellowing of normally green tissue resulting from chlorophyll destruction or failure to develop.

Coleoptile Sheath-like structure enclosing the shoot of a grass seeding for a short time after germination.

Collar Juncture of leaf blade and sheath; may be used to identify grass species.

Commingled rice Blend of rice of similar grain type, quality, and grade.

Culm Stem of a grass plant; rice plants have main culms and tiller culms.

Dough stage Stage of maturity when a grain develops from a thick liquid to a soft dough consistency.

Embryo Microscopic plant attached to the endosperm of a seed; often called the germ.

Endosperm Stored food, primarily a carbohydrate in the form of starch, comprising most of a monocot seed such as rice; the endosperm serves as food for the embryo and developing seedling during germination and early growth.

Flag leaf Topmost leaf of the rice plant immediately below the panicle.

Floret Grass flower, including the lemma, palea, and sex organs.

Green rice High moisture (18.5 to 22.5%) rough rice.

Hailing Removal of the lemma and palea (husks or hulls) from rough rice.

Head milling yield Pounds of head rice milled from 100 lb of rough rice.

Head rice Milled rice kernel comprising more than 3/4 of the whole kernel.

Hull Lemma and palea parts of rough rice that are usually waste products but may be used in rice millfeed and as filler in feed products.

Inflorescence Flowering structure of a plant.

Instant rice Milled rice that has been cooked, cooled, and dried under controlled conditions and packaged in dehydrated form; requires little preparation time before eating; enriched with thianline, riboflavin, niacin, and iron.

Internode Area of a stem between two nodes.

Jointing Internode elongation in grasses.

Lemma The larger of two structures enclosing a rice seed; with the palea, it forms the hard outer covering of rough rice.

Ligule Short membranous projection on the inner side of a leaf blade at the junction of blade and sheath in many grasses.

Long-grain rice
Long slender rice; when milled, measures typically from 0.26 to 0.28 in. (6.7 to 7.0 mm) or longer; has length:width ratio from 3.27 to 3.41:1.

Main culm or shoot Stem or above-ground portion of a plant originating directly from seed.

Medium-grain rice Rice that, when milled, measures typically from 0.22 to 0.23 inches (5.5 to 5.8 mm); has length:width ratio of 2.09 to 2.49:1.

Milk stage Early stage of grain development when milky liquid fills the grain.

Milled rice Grain with husks, bran, and germ removed.

Milling Converting rough rice into milled or brown rice.

Necrotic Dead.

Nematode Unsegmented, round, thread-like, usually microscopic worm that may be free-living or parasitic on plants and animals; soil-inhibiting nematodes may be parasitic on rice.

Node Solid portion of the rice stem from which leaves arise.

Paddy Subdivision of a rice field; bounded by levees.

Palea The smaller of two enclosing structures forming a hard outer covering of unmilled rice.

Panicle Many-branched inflorescence composed of few to many spikelets containing one to several florets.

Parboiled rice Rough rice steeped in warm water under pressure, steamed, dried, and milled; improves head milling yield.

Pathogen Living organism that causes infectious disease.

Precooked rice Milled rice processed to make it cook quickly.

Processed rice Rice used in breakfast cereals, soups, baby foods, packaged mixes, etc.

Ratoon crop Second crop; regrowth from stubble of a first crop that grew from seed.

Residue management Management of rice straw and stubble after harvest; residue of previous crop before planting.

Rice bran Outer layer of the caryopsis just beneath the hull containing the outer bran layer and parts of the germ; rich in protein and vitamin B; used as livestock feed and in vitamin concentrates.

Rice polish Layer composed of the inner white bran and perhaps aleurone cells that are high in protein and fat; used in livestock feed and baby food; sometimes removed at the final stage of milling.

Rough or paddy rice Rice grains with hulls but without stalk parts; consists of 50% or more whole or broken unhulled kernels.

Screenings Broken milled rice kernels containing less than 1/2 and more than 1/4 of the whole kernel.

Second heads Broken milled rice kernels containing more than 1/2 and less than 3/4 of the whole kernel.

Senescence Stage of growth from maturity to death.

Sheath Portion of a complete grass leaf below the collar that may enclose the stem.

Shoot Above-ground portion of a plant; in rice, the portion above the crown.

Short-grain rice Rice that is almost round and when milled measures typically from 0.20 to 0.22 inches (5.2 to 5.4 mm); has a length:width ratio of 1.66 to 1.77:1.

Spikelet Subdivision of a spike consisting of one to several flowers.

Tiller Vegetative shoot, not the main culm.

Total milling yield Pounds of heads, second heads, brewers, and screenings milled from 100 lb rough rice.

White rice Kernel remaining after hull, bran layer, and germ are removed; includes head rice and brokens.

Y leaf Most recently matured leaf.

2.5.3 Production Statistics

TABLE 2.72
Leading Rice-Growing Countries, 1999–2000

Country	1,000 Short Tons
China	206,335
India	121,418
Indonesia	31,740
Bangladesh	30,451
Vietnam	22,337
Thailand	21,708
Myanmar	16,708
Japan	12,865
Brazil	10,908
Philippines	10,410

Source: United Nations Food and Agriculture Organization, Rome.

TABLE 2.73
Milled Rice: Acreage, Yield, and Production in Continents and Specified Countries, 2000[a]

Location	Harvested Area (1,000 ha)	Yield (metric tons/ha)	Production (1,000 metric tons)
Continent			
North America	1,511	4.50	6,802
South America	5,452	2.41	13,122
Central America	255	2.22	567
Caribbean	220	2.34	514
European Union	396	4.36	1,725
Eastern Europe	23	1.52	35
Soviet Union	473	1.63	773
Middle East	750	2.57	1,930
Africa	7,160	1.48	10,581
Asia	137,860	2.68	369,376
Oceania	134	5.78	775
Country			
India	44,500	2.01	89,480
China	31,284	4.44	138,936
Indonesia	11,650	2.87	33,445
Bangladesh	10,700	2.01	21,530
Thailand	10,080	1.64	16,500
Vietnam	7,660	2.71	20,750
Myanmar	5,800	1.70	9,860
Philippines	3,995	1.95	7,772
Brazil	3,650	2.15	7,843
Pakistan	2,515	2.05	5,156
Cambodia	2,120	1.13	2,400
World Total	154,234	2.63	406,200

[a] Crop yield beginning August 1.

Source: Estimate and Crop Assessment Division, Foreign Agriculture Service, Washington, D.C.

TABLE 2.74
Rice by Length of Grain: U.S. Acreage, Yield, and Production, 1999–2000

State	Area Harvested (1,000 acres)	Yield (lb/acre)	Production (1,000 cwt)
		Long Grain	
Arkansas	1,175	6,060	71,205
California	5	7,100	365
Louisiana	455	5,080	23,114
Mississippi	218	5,900	12,862
Missouri	173	5,700	9,861
Texas	209	6,740	14,087
		Medium Grain	
Arkansas	233	6,300	14,679
California	513	8,000	41,040
Louisiana	25	5,150	1,288
Missouri	1	5,700	57
Texas	5	5,100	255
		Short Grain	
Arkansas	2	6,000	120
California	30	7,300	2,190

Source: Crops Branch, National Agriculture Security Service, Washington, D.C., 2001.

TABLE 2.75
Rough Rice: U.S. Acreage, Yield, and Production, 1991–2000

Year	Area Harvested (1,000 acres)	Yield (lb/acre)	Production (1,000 cwt)
1991	2,761	5,731	159,367
1992	3,132	5,736	179,658
1993	2,833	5,510	156,110
1994	3,316	5,964	197,779
1995	3,093	5,621	173,871
1996	2,604	6,120	171,599
1997	3,103	5,897	182,992
1996	3,257	5,663	184,443
1999	3,512	5,866	206,027
2000	3,044	6,276	191,113

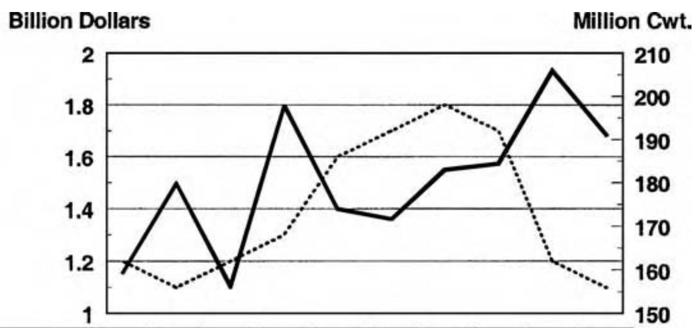
Source: Crops Branch, National Agriculture Security Service, Washington, D.C., 2001.

TABLE 2.76
Rice and Milled Rice Products: U.S. Total and Per Capita Civilian Consumption, 1990–1999

Marketing Year (August 1–July 1)	Total Consumed (cwt)	Per Capita Consumption (lb)
1990	42.7	17.0
1991	43.7	17.2
1992	45.4	17.7
1993	49.6	19.1
1994	51.5	19.7
1995	52.6	19.9
1996	53.7	20.1
1997	55.0	20.4
1998	56.8	20.9
1999[a]	59.3	21.6

[a] Preliminary.

Source: Economics Research Service, Washington, D.C., 2001. All figures are estimates based on data from private industry sources, the U.S. Department of Commerce, the Internal Revenue Service, and other government agencies.



Year	91	92	93	94	95	96	97	98	99	00
Production —	159.4	179.7	156.1	197.8	173.9	171.6	183.0	184.4	206.0	191.1
Value of Prod. ···	1.2	1.1	1.2	1.3	1.6	1.7	1.8	1.7	1.2	1.1

FIGURE 2.13 Rough rice: Production and value of production, 1991–2000.

2.5.4 Grain Quality

TABLE 2.77
Food Value of White Rice

Component	%
Carbohydrate	80.4
Water	12.0
Protein	6.7
Ash	0.5
Fat	0.4

TABLE 2.78
Nutritive Value of Whole Grain

Component	Value
Calories/100 g	363
Protein,%	6.7
Fat,%	0.2
Total calcium, mg/lb	24
Total phosphorus, mg/lb	94
Total potassium, mg/lb	92
Carbohydrates,%	80.4

2.5.5 Nutrient Element Deficiencies

TABLE 2.79
Nutrient Element Deficiency Symptoms and Effects on Rice Growth

Nutrient Element	Symptoms and Effects on Growth
Nitrogen	Stunted, yellowish plants; yellowish green older leaves or whole plants
Phosphorus	Stunted dark green plans with erect leaves and reduced tillering
Potassium	Dark green plants with yellowish brown leaf margins or dark brown necrotic spots first appearing on the tips of older leaves
Calcium	Chlorotic-necrotic split leaves or rolled tips on younger leaves
Magnesium	Orange-yellow interveinal chlorosis on older leaves
Sulfur	Pale green plants; light green-colored young leaves
Silicon	Soft, droopy leaves and culms
Boron	White, rolled tips of young leaves
Copper	Chlorotic streaks and bluish green leaves that become chlorotic near the tips
Iron	Interveinal yellowing and chlorosis
Zinc	Dusty brown spots on upper leaves of stunted plants appearing 2 to 4 weeks after transplanting

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

TABLE 2.80
Element Toxicity Symptoms and Effects on Growth

Element	Symptoms and Effect on Growth
Aluminum	Orange-yellow interveinal chlorosis on leaves; poor growth, stunted plants
Boron	Brownish leaf tips and dark brown elliptical spots on leaves
Iron	Tiny brown spots on lower leaves starting from the tips or whole leaves colored orange-yellow to brown; black coating on root surfaces
Manganese	Yellowish brown spots between leaf veins, extending to interveinal areas
Sulfide	Interveinal chlorosis of emerging leaves; coarse, sparse, and blackened roots

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

TABLE 2.81
Silicon Fertilizer Sources

Substance	Formula	Silicon Content	Comment
Blast furnace slag	$CaSiO_3$, $MgSiO_3$	14–19% Si, 25–32% Ca, 2–4% Mg	
Convertor slag	$CaSiO_3$, $MgSiO_3$	4–10% Si, 26–46% Ca, 0.5–9% Mg	
Silico-manganese slag	$CaSiO_3$, $MnSiO_3$	16–21% Si, 21–25% Ca, 0.5–2% Mn	
Fused magnesium phosphate		9% Si, 9% P, 7–9% Mg	Granular
Calcium silicate	Si, Ca, Mg	14–19% Si, 1–4% Mg	Granular, slow-release fertilizer
Potassium silicate	K, Si	14% Si, 17% K, 2.5% Mg	Granular, slow-release fertilizer

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

2.5.6 Fertilizer and Nutrient Element Status

TABLE 2.82
General Soil- and Season-Specific Fertilizer Recommendations (kg/ha) for Irrigated Rice

	Dry Season (Y_{max} ~ 10 tons/ha)			Wet Season (Y_{max} ~7.5 tons/ha)		
Target Yield	N	P	K	N	P	K
Low Soil Fertility						
4	60–80	8–12[a]	20–40	60–80	8–12[a]	20–25
5	90–110	15–25	50–60	90–120	15–25	50–60
6	120–150	25–40	80–100	Yield target not applicable		
7	150–200[b]	35–60	110–140			
Medium Soil Fertility						
4	0[a]	8–12[a]	10–40[a]	0[a]	8–12[a]	10–40[a]
5	50–70	10–15[a]	15–50[a]	50–70	10–15[a]	15–50[a]
6	90–110	12–18	30–60	100–120	12–18	40–60
7	120–150	15–30	60–80	Yield target not applicable		
8	160–200[b]	35–50	110–130			
High Soil Fertility						
4	0[a]	8–12[a]	10–40[a]	0a	8–12[a]	10–40[a]
5	0[a]	10–15[a]	15–50[a]	20–30	10–15[a]	15–50[a]
6	50–60	12–18[a]	20–60[a]	60–80	12–18[a]	20–60[a]
7	80–100	14–21[a]	20–70[a]	Yield target not applicable		
8	120–150	15–25	60–80			

[a] Indigenous supply of P and K sufficient to achieve this yield level with smaller or no fertilizer application. For N, this is a situation where input from other sources such as biological N_2 fixation is large enough to sustain the INS at this level. For P and K, we recommend applying amounts of P and K at least equivalent to the net P and K removal from the field with grain and straw to maintain soil P and K supplies. The values given assume a replenishment dose equivalent to P removal of 2–3 kg P/ha and K removal of 3–10 kg K/ha/ton of grain yield. The smaller value applies to systems in which most of the P and K in straw remains in the field, either incorporated or burned. The larger value applies to systems with large removals of crop residues.

[b] Caution: N dose recommended is very large and could cause lodging and increased pest incidence.

Source: QUBFTS model modified for rice. For each yield target, the model was run using the INS, IPS, and IKS assumed for each soil type and the ranges of recovery effciencies of N, P, and K specified above.

TABLE 2.83
Effect of Nutrient Availability on the Removal of N, P, and K (kg Nutrient/ton of Rice Grain) for the Linear Part of the Relationship of Grain Yield and Nutrient Uptake (<80% of Potential Yield)

Nutrient Element Availability	Nitrogen	Phosphorus	Potassium
Maximum nutrient limitation	10	1.6	9
Nutrient limitation	11–13	1.7–2.3	10–13
Nutritional optimum	14–16	2.4–2.8	14–16
Nutrient surplus	17–23	2.9–4.8	17–27
Maximum nutrient surplus	24	4.9	28

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

TABLE 2.84
Optimal Internal Efficiency (kg/grain/kg Element) of N, P, and K in Irrigated Rice

N	P	K
68	385	69

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

TABLE 2.85
Uptake of Major Elements and Micronutrients for 7.8 Tons/Acre Crop

Major Elements	kg
Nitrogen	125
Phosphorus as phosphate	67
Potassium as potash	130
Calcium	23
Magnesium	16
Sulfur	21
Micronutrients	**g**
Boron	60
Copper	20
Iron	810
Manganese	600
Molybdenum	2
Zinc	215

Source: International Soil Fertility Manual. 1995. Potash & Phosphate Institute, Norcross, GA.

TABLE 2.86
Nitrogen, Phosphorus, and Potassium Uptake and Content in Modern Rice Varieties

Plant Part	Typical Observed Range[a]	Observed Average[b]
	kg N uptake/ton grain yield	
Grain + straw	15–20	17.5
Grain	9–12	10.5
Straw	6–8	7.0
	% N content	
Grain	0.93–1.20	1.06
Straw	0.51–0.76	0.63
Unfilled spikelets	0.76–1.02	0.89
	kg P uptake/ton grain yield	
Grain + straw	2.5–3.5	3.0
Grain	1.7–2.3	2.0
Straw	0.8–1.2	1.0
	% P content	
Grain	0.18–0.26	0.21
Straw	0.07–0.12	0.10
Unfilled spikelets	0.13–0.20	0.17
	kg K uptake/ton grain yield	
Grain + straw	14–20	17.0
Grain	2–3	2.5
Straw	12–17	14.5
	% K content	
Grain	0.22–0.31	0.27
Straw	1.17–1.68	1.39
Unfilled spikelets	0.61–1.20	1.07

[a] 25–75% interquartile range of farmers' fields and field experiments in Asia (n = 1,300).
[b] Median of farmers' fields and field experiments in Asia (n = 1,300).

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

2.5.7 Nutrient Element Sufficiency

TABLE 2.87
Optimal Ranges and Critical Levels for Occurrence of Mineral Deficiencies or Toxicities in Tissue

Nutrient Element	Growth Plant Stage	Plant Part	Optimum Range	Critical Level for Deficiency	Critical Level for Excess or Toxicity
				%	
Nitrogen	Tillering-PI	Y leaf	2.9–4.2	<2.5	>4.5
	Flowering	Flag leaf	2.2–2.5	<2.0	
	Maturity	Straw	0.6–0.8		
Phosphorus	Tillering-PI	Y leaf	0.20–0.40	<0.10	>0.50
	Flowering	Flag leaf	0.20–0.30	<0.18	
	Maturity	Straw	0.10–0.15	<0.06	
Potassium	Tillering-PI	Y leaf	1.8–2.6	<1.5	>3.0
	Flowering	Flag leaf	1.4–2.0	<1.2	
	Maturity	Straw	1.5–2.0	<1.2	
Calcium	Tillering	Y leaf	0.2–0.6	<0.15	>0.7
	Tillering-PI	Shoot	0.3–0.6	<0.15	
	Maturity	Straw	0.3–0.5	<0.15	
Magnesium	Tillering-PI	Y leaf	0.15–0.30	<0.12	>0.50
	Tillering-PI	Shoot	0.15–0.30	<0.13	
	Maturity	Straw	0.20–0.30	<0.10	
Sulfur	Tillering	Y leaf	<0.15		
	Tillering	Shoot	0.15–0.30	<0.11	
	Flowering	Flag leaf	0.10–0.15	<0.10	
	Flowering	Shoot	<0.07		
	Maturity	Straw	<0.06		
Silicon	Tillering	Y leaf	<5		
	Maturity	Straw	8–10	<5	
				mg/kg	
Boron	Tillering	Y leaf	6–15	<5	>100
	Maturity	Straw	<3	>100	
Copper	Tillering	Y leaf	7–15	<5	>25
	Maturity	Straw	<6	>30	
Iron	Tillering	Y leaf	75–150	<70	>300
	Tillering	Shoot	60–100	<50	
Manganese	Tillering	Y leaf	40–700	<40	>800
	Tillering	Shoot	50–150	<20	
Zinc	Tillering-PI	Y leaf	25–50	<20	>500
	Tillering	Shoot	25–50	<10	>500
Aluminum	Tillering	Shoot	15–18	<5	>100

Note: PI = panicle initiation.

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

TABLE 2.88
Nutrient Element Sufficiency Ranges

	Sufficiency Range	
Nutrient Element	Panicle Initiation	Maximum Tillering
	%	
Nitrogen	2.60–3.20	2.80–3.60
Phosphorus	0.09–0.18	0.10–0.18
Potassium	1.00–2.20	1.20–2.40
Calcium	0.20–0.40	0.15–0.30
Magnesium	0.20–0.30	0.15–0.30
	ppm	
Boron	6–10	5–15
Copper	8–25	8–25
Iron	70–150	75–200
Manganese	150–800	200–800
Zinc	18–50	25–50

Note: Sampling procedure = 25 mature leaves from new growth.

Source: *Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide*, 1996, MicroMacro Publishing, Athens, GA.

TABLE 2.89
Typical Symptoms Associated with Most Common Deficiencies

Nutrient Element	Mobility	Symptoms
Nitrogen	Mobile	Older leaves become pale green to yellow; younger leaves greener and may be narrow, short, and erect; plants are stunted with few tillers
Phosphorus	Mobile	Leaves become dark green to purple, narrow, short and erect; later become necrotic; plants are stunted with few tillers
Potassium	Mobile	Leaves become dark green followed by interveinal chlorosis and small necrotic spots coalescing from tips; leaves are shortened and slightly smaller
Sulfur	Mobile	Similar to N
Iron	Immobile	Starts as interveinal chlorosis on young leaves; entire leaves become pale yellow to whitish; older leaves remain green
Zinc	Immobile	Midribs of younger leaves turn yellow and droop, stunted growth and delayed maturity

Source: Crop Production: Evolution, History, and Technology, 1995, John Wiley & Sons, New York.

2.5.8 Weights and Measures

TABLE 2.90
Rice Seeds/Pound, Weight/Bushel, and Germination Time

Seeds/lb (1,000)	Seeds/g (no.)	Weight/bu	Germination Time (days)
15	65	45	14

TABLE 2.91
Weights and Measures

Unit	Approximate Net Weight lb	Approximate Net Weight kg
Rough rice		
Bu	45	20.4
Bag	100	45.4
Bbl	162	73.5
Milled rice		
Cook-in-bag	100	45.4

Source: U.S. Department of Agriculture, Agricultural Statistics, 2001, U.S. Government Printing Office, Washington, D.C.

REFERENCES

1. *Rice Inspection Handbook*.
2. Smith, C.W., *Crop Production: Evolution, History, and Technology*, 1995, John Wiley & Sons, New York.

2.6 WHEAT (*Triticum aestivum* L., *T. durum* Desf.)

2.6.1 Introduction

Wheat is a member of the Poaceae or Graminae grass family. It is known as blé in France, trigo in Spain, frumento in Italy, and wreizen in Germany. It was one of the earliest crops cultivated and dates back to 11,000 B.C. in the Middle East. By about 4,000 B.C., wheat farming had spread to Asia, Europe, and northern Africa. In 1493, wheat was brought to the Americas. It reached Mexico in 1519 and Argentina by 1527. The spread of cultivation followed the movements of missionaries, colonists, pioneers, and religious groups into Canada and the U.S. The introduction of winter wheat in the U.S. in the 1870s greatly increased production.

`In 1988, the highest verifiable winter wheat grain yield of 190 bu per acre was recorded in British Columbia, Canada. In the U.S. in 2000, the average winter wheat yield was 41.9 bu per acre and the highest average state yield was 61.8 bu per acre in the state of Washington.

Wheat covers more cultivated land (232 million ha) than any other food crop and is one of the most important (595 million tons). It grows in a wide range of climates (best in fairly dry and mild climates) and soils (best grown on clay and silt loams). In most wheat-growing areas, farmers grow

the crop on the same land every year. This produces soil fertility problems and increased protential for water and wind erosion. The grain is harvested when its moisture level is not more than 14%.

Harvested products include or are made into bran, bread, flour, gluten, pasta, starch, and straw for litter and bedding. Plants are sometimes harvested for grazing or fodder. Hard red wheats generally make excellent bread flour, cakes, cookies, and pastries, Durum wheats are best in pasta products, and white wheats are used in breakfast foods and pastries.

2.6.2 Glossary[1]

Blending Combining measured amounts of different lots from bins and mixing them into a uniform blend with grain assemblers or millers.

Bolt Sift through a cloth or sieve.

Bran Outer covering of a wheat kernel composed of seed coat, nuclear tissue, tube and cross cells, hypodermis, and endodermis, which are separated from the endosperm and embryo or germ during commercial milling.

Break flour Flour produced by break rolls during commercial milling; particles of endosperm are also reduced to flour.

Break system Stage in the milling process in which kernels are broken by a series of successively closer-set pairs of rollers to separate the endosperm from the bran coat.

Broken kernel Kernel separated into two or more pieces, exclusive of insect boring or surface consumption.

Clear flour Flour remaining after a patent flour has been removed; normally higher in ash and protein than patent but of lower market value because of color.

Club wheat *Triticum aestivum* subsp. *compactum*: usually white wheat cultivars; may be winter or spring; heads are usually awnless, elliptical, oblong, or clavate in shape, and short, compact, or laterally compressed.

Coarse break Break roll that grinds larger particles in a classified break system in which break stock is classified as coarse and fine by size and ground on separate rolls.

Crop year U.S. officially designated production–marketing year for a commodity; the wheat crop year is June 1 to May 31.

Durum wheat *Triticum turgidum* subsp. *durum*; has 14 pairs of chromosomes; spring growth habit; very hard; high protein; used primarily for pasta.

Elevator Point of accumulation and distribution in the movement of grain; terminal elevators usually receive grain by railroad carloads; country elevators receive grain by trucks, usually from farmers.

Endosperm Starchy portion of the wheat kernel that is ground into flour; the seed-stored nutrient supply for the embryo during germination and early seedling growth.

Ethanol Grain alcohol made from almost any kind of grain containing a reasonable amount of starch.

Family flour Commonly called all-purpose flour; used for baking bread, cakes, biscuits, etc.

Fancy patent flour Most finely ground flour.

Farina Very pure endosperm of nondurum wheat ground to about medium screen size; maybe used in pasta, but will overcook more easily than pasta made from durum wheat

Fine break Break roll used to further reduce smaller particles in a classified break system of milling.

First clear Portion of straight run flour remaining after patent flour has been removed; higher in protein than the patent flour produced but poorer in color and thus has lower commercial value; about 20 to 25% of the flour produced in hard wheat mills may be first clear.

Flour extraction rate Percent of flour produced from milling 100 lb of wheat kernels.

Gluten Rubber-like proteinaceous material in wheat that gives wheat its superior bread-making quality; a measure of flour quality; a third of the weight of wet gluten approximates the protein content of the flour.

Grain reserve Wheat stored by the U.S. government.

Hard red spring (HRS) *Triticum aestivum* subsp. *aesrivum*; also called common or bread wheat; has 21 chromosome pairs — A, B, and D genomes; spring seeded; not winter hardy; does not require vernalization for reproduction; may be referred to as red, dark northern, or northern; high protein; hard endosperm; primarily used to produce bread flour.

Hard red winter (HRW) *Triticum aestium* subsp. *aestivum*, also called common or break wheat; has 21 chromosome pairs — A, B, and D genomes; fall seeded; winter hardiness varies; requires vernalization for reproduction; may be referred to as dark hard, hard, or yellow hard; medium to high protein; hard endosperm; primarily used to produce bread flour.

Hard wheat Generic term for wheat having a vitreous endosperm suitable for bread flour or semolina; yields coarse, gritty flour that is free-flowing and easily sifted; flour consists of regular shaped particles that are mostly whole endosperm cells.

Middlings Pieces of endosperm not ground into flour; a byproduct of commercial milling produced during break reduction and composed of coarse material; usually used for animal feed.

Middlings rolls Pair of smooth rolls used to reduce middlings to flour particle size; may be called reduction rolls.

Millfeed Any byproduct of the milling industry used as livestock feed.

Pasta Product made principally from durum wheat flour; includes macaroni, spaghetti, and noodles.

Patent flour Highest value grade flour with good dress and color.

Product stream Any of 125 to 150 mill streams in the flour manufacturing process; different grades of flour are produced by blending individual streams.

Semolina Coarse endosperm extracted from durum wheat; used for pasta.

Short An inseparable mixture of bran, endosperm, and wheat germ remaining after flour extraction in milling; used for animal feed.

Soft red winter (SRW) *Triticum aestivum* subsp. *aestium*; a common wheat; has 21 chromosome pairs — A, B, and D genomes; fall seeded; winter hardiness varies; requires vernalization for reproduction; low to medium protein; soft or floury endosperrn; used primarily for cakes, pastries, and products whose tenderness is important.

Soft wheat Generic term for wheat having a chalky, nonvitreous endosperrn suitable for pastry flour; yields a very fine flour consisting of irregular-shaped fragments of endosperm cells that cling together and are difficult to shift.

Spring wheat Wheat seeded in the spring and harvested the following summer or fall; does not require vernalization to reproduce.

Stock Wheat in storage or transit; stock sometimes includes processed products in inventory.

Straight flour Flour extracted from a blend or mill mix of wheat without division or addition of flour from other runs.

Test weight Quality test used to determine weight per bushel; bushel weight standard for wheat is 60 pounds.

Vernalization Low temperature-triggered, hormonal-controlled conversion from vegetative growth to reproductive growth in winter wheat; requires temperatures below 50°F; length of exposure required is cultivar-dependent.

2.6.3 Production Statistics

TABLE 2.92
Wheat: Area, Yield, and Production, 1999–2000[a]

Continent	Harvested Area (1,000 ha)[b]	Yield (metric tons/ha)	Production (1,000 metric tons)
North America	32,845	2.82	92,519
South America	8,132	2.48	20,179
Europe	17,016	5.71	97,115
Eastern Europe	8,346	3.47	28,951
Western Europe	158	5.64	891
Soviet Union	42,225	1.58	66,510
Middle East	17,690	1.72	30,482
Africa	9,295	1.78	16,583
Asia	68,724	3.05	209,422
Oceania	12,393	2.04	25,287
World Total	216,827	2.71	587,944

[a] Year of harvest.
[b] Harvested area.

Source: Foreign Agriculture Service, Washington, D.C.

TABLE 2.93
Area, Yield, and Production of Leading Wheat-Growing Countries, 1999–2000[a]

Country	Harvested Area (1,000 ha)[b]	Yield (metric tons/ha)	Production (1,000 metric tons)
China	28,855	3.95	113,880
India	27,400	2.58	70,780
Russia	23,000	1.36	31,000
U.S.	21,781	2.87	62,569
Australia	12,338	2.03	25,012
Canada	10,364	2.59	26,850
Kazakhstan	8,730	1.28	11,200
Turkey	8,650	1.91	16,500
Pakistan	8,231	2.17	17,854
Iran	6,000	1.42	8,500
Ukraine	5,900	2.29	13,599
France	5,116	7.28	37,232
World Total	216,827	2.71	587,944

[a] Year of harvest.
[b] Harvested area.

Source: Foreign Agriculture Service, Washington, D.C.

TABLE 2.94
Area, Yield, and Production of Leading States, 2000

State	Harvested Area (1,000 acres)	Yield (bu/acre)	Production (1,000 bu)
North Dakota	9,413	33.3	313,785
Kansas	9,400	37.0	347,800
Montana	4,920	27.5	135,250
Oklahoma	4,200	34.0	142,800
South Dakota	2,878	39.7	114,268
Washington	2,420	68.1	164,880
Colorado	2,396	29.8	71,370
Texas	2,200	30.0	66,000
Minnesota	1,971	49.0	96,926
Nebraska	1,650	36.0	59,400
U.S. Total	53,028	41.9	2,223,440

Source: Crops Branch, National Agriculture Statistics Service, Washington, D.C.

TABLE 2.95
U.S. Total and Per Capita Civilian Consumption of Wheat and Wheat Products, 1990–1999

		Per Capita Consumption of Food Products	
Calendar Year	Total Consumed (million bu)[a]	Flour (lb)[b]	Cereal (lb)
1990	773	136	4.3
1991	791	137	4.5
1992	817	139	4.7
1993	853	143	5.0
1994	871	144	5.2
1995	858	142	5.4
1996	896	149	5.4
1997	902	150	5.4
1998	911	148	5.4
1999	919	147	5.3

[a] Excludes quantities used alcoholic beverages.
[b] Includes white, whole wheat, and semolina flour.

Source: Economics Research Service, Washington, D.C. All figures are estimates based on data from private industry sources, the U.S. Department of Commerce, the Internal Revenue Service, and other government agencies.

TABLE 2.96
U.S. Wheat Acreage, Yield, and Production, 1991–2000[a]

Year	Harvested Acres (1,000)	Yield (bu/acre)[b]	Production (1,000 bu)
1991	57,803	34.3	1,980,139
1992	62,761	39.3	2,466,798
1993	62,712	38.2	2,396,440
1994	61,770	37.8	2,320,981
1995	60,955	35.8	2,182,706
1996	62,819	38.3	2,277,388
1997	62,640	39.5	2,461,466
1998	59,002	43.2	2,547,321
1999	53,823	42.7	2,299,010
2000	53,028	41.9	2,223,440

[a] Includes area seeded in preceding fall for winter wheat.
[b] Includes allowance for loans outstanding and purchases by the government valued at the average loan and purchase rate by state where applicable.

Source: Crops Branch, National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 2.97
Harvest Times for Wheat Crops

January	Argentina, Australia. Chile, New Zealand
February	Myanmar, Chile, New Zealand, Uruguay
March	India, Upper Egypt
April	Lower Egypt, India, Iran, Mexico, Morocco
May	Algeria, China, Japan, Spain, southwestern U.S.
June	China, southern France, Greece, Italy, Portugal, Spain, Tunisia, Turkey, southern U.S.
July	Bulgaria, Croatia, southern England, France, Germany, Hungary, Kazakhstan, Moldova, Romania, Russia, Urkaine, northern U.S.
August	Belgium, Canada, Denmark, northern England, Kazahkstan, Moldova, Netherlands, Russia, Ukraine, northern U.S.
September and October	Canada, Kazakhstan, Russia, Scandinavia, Scotland
November	Argentina, Brazil, Venezuela, South Africa
December	Argentina, Australia

TABLE 2.98
Varieties of U.S.-Grown Wheat

Variety	States Where Grown
Hard red winter	Texas, Oklahoma, Kansas, Colorado, Nebraska
Hard red spring	Minnesota, South Dakota, North Dakota, Montana
Spring durum	Northern Great Plains, Arizona, California
Soft red winter	Missouri, Illinois, Indiana, Ohio, Pennsylvania
White	Michigan, New York, California, Washington, Oregon, Idaho

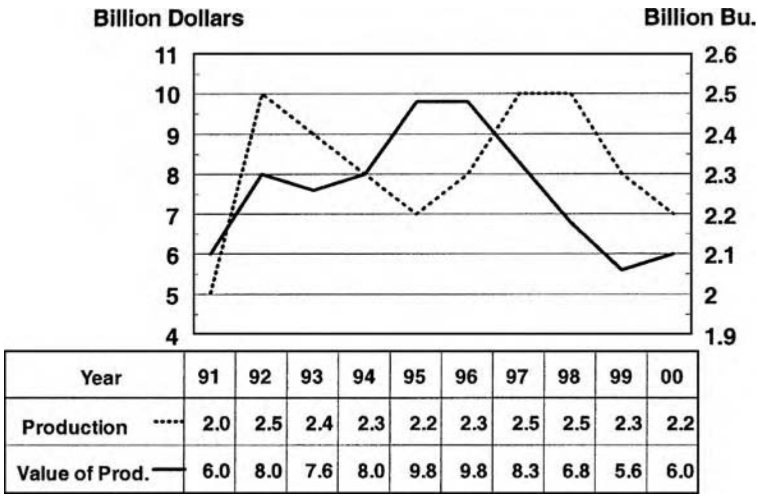


FIGURE 2.14 Wheat production and value of production in the U.S., 1991–2000.

2.6.4 Grain Quality

TABLE 2.99
Average Composition (%) of Wheat Flour, Bran, and Germ Containing about 13% Moisture

Composition	Wheat or Graham Flour	White Flour	Bran	Germ
Carbohydrates				
Nitrogen-free extract	68	74	50	18
Starch	55	70	10	—
Pentosans	6	3.5	25	—
Dextrins	—	—	4	—
Sugars	2	1.5	1.5	15
Crude fiber	2.3	0.4	9	2
Fat	2	1	4	11
Crude protein	13	11	17	30
Ash (mineral matter)	2	0.45	7	5

TABLE 2.100
Quality Components of Wheat Grain

Component	Value
Digestible energy, kcal/kg	3,520
Protein, %	13.7
Lysine, %	0.45
Methionine + cystine, %	0.36
Tryptophan, %	0.18
Calcium, %	0.05
Phosphorus, %	0.36
Fiber, %	3.0
Ether extract, %	1.7

2.6.5 Fertilizer Use

TABLE 2.101
Fertilizer, Total Acreage, and Area Receiving Applications (%), All States Surveyed, 1995–1999[a]

Crop Type	Nitrogen	Phosphate	Potash
1995			
Wheat, winter	86	54	16
Wheat, durum	92	78	10
Wheat, other spring	87	78	23
1996			
Wheat, winter	86	51	6
Wheat, durum	93	73	8
Wheat, other spring	89	79	24
1997			
Wheat, winter	84	53	15
Wheat, durum	95	77	8
Wheat, other spring	92	82	25
1998			
Wheat, winter	89	63	22
Wheat, durum	94	76	5
Wheat, other spring	87	77	25

[a] Acres receiving one or more applications of a specific fertilizer ingredient.

Source: National Agriculture Statistics Service, Washington, D.C.

2.6.6 Elemental Uptake and Utilization

TABLE 2.102
Nutrient Elements Removed by a Bushel of Wheat

Nutrient Element	Amount Removed	
	Grain	Grain + Straw
Nitrogen, lb/bu	1.20	1.52
Phosphorus as phosphate, lb/bu	0.56	0.70
Potassium as potash, lb/bu	0.31	1.03
Sulfur, lb/bu	0.12	0.22
Calcium, lb/bu	0.05	0.25
Magnesium, lb/bu	0.13	0.35
Copper, oz/bu	0.012	—
Manganese, oz/bu	0.036	—
Zinc, oz/bu	0.055	—

Source: *Crop Production: Evolution, History, and Technology*, 1995, John Wiley & Sons, New York.

TABLE 2.103
Nutrient Elements (lb/acre) Removed by Wheat Crop

Nutrient Element	Grain (60 bu/acre)	Straw (2 tons/acre)
Nitrogen	75	30
Phosphate	39	9
Potash	24	65
Sulfur	5	7
Calcium	2	9
Magnesium	9	5
Boron	0.06	0.02
Copper	0.05	0.03
Iron	0.45	0.15
Manganese	0.14	0.26
Zinc	0.2	0.08

TABLE 2.104
Uptake of Major Elements and Micronutrients for 4-Ton/Acre Wheat Crop

Major Element	kg	Micronutrient	g
Nitrogen	130	Boron	36
Phosphorus as phosphate	46	Copper	43
Potassium as potash	180	Iron	380
Calcium	18	Manganese	120
Magnesium	20	Zinc	180
Sulfur	17		

Source: International Soil Fertility Manual, 1995, Potash & Phosphate Institute, Norcross, GA. With permission.

TABLE 2.105
Nutrient Element Utilization by 40-Bu/Acre Wheat Crop

Nutrient Element	Content (lb)
Nitrogen	160
Phosphorus as phosphate	54
Potassium as potash	184
Magnesium	24
Sulfur	20

2.6.7 Nutrient Element Sufficiency

TABLE 2.106
Nutrient Element Sufficiency Ranges for Wheat

	Sufficiency Range	
Nutrient Element	**Spring Wheat[a]**	**Winter Wheat[b]**
Nitrogen, %	2.00–3.00	1.75–3.00
Phosphorus, %	0.20–0.50	0.20–0.50
Potassium, %	1.50–3.00	1.50–3.00
Calcium, %	0.20–0.50	0.20–1.00
Magnesium, %	0.15–0.50	0.15–1.00
Boron, ppm	6–10	—
Copper, ppm	5–25	5–50
Iron, ppm	25–00	10–300
Manganese, ppm	25–100	16–200
Molybdenum, ppm	0.09–0.18	—
Zinc, ppm	15–70	20–70

[a] As head emerges from boot; 50 leaves, top 2 leaves.
[b] Just before heading; 25 whole tops.

Source: Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide, 1996, MicroMacro Publishing, Athens, GA. With permission.

2.6.8 Nutrient Element Deficiencies

2.6.8.1 Calcium (Ca)

2.6.8.1.1 Deficiency Symptoms

Calcium-deficient plants are very stunted with short, stout stems and dark green leaves that are held erect. Although tiller production does not appear to be affected by mild deficiencies, few tillers may mature and produce heads. When a deficiency is severe, plants die before heads are produced. As a result, grain yields can be greatly reduced.

Weather-tipped young leaves: Because Ca is not transferred from old to young leaves when a deficiency occurs, symptoms appear first and are more severe on young leaves. They are often most severe on the youngest, still unrolling leaves. All leaves are dark green and the tips of the youngest leaves turn yellow, then grey or pale brown, and die. The dead tissue becomes tightly rolled into tubes and may twist into circles. Affected leaves are very brittle and the laminae may tear while emerging or the dead tips may break off to produce squared ends of the leaves. The bases of affected leaves remain dark green and appear healthy. Mature leaves remain unaffected and retain their healthy, dark green appearance.

Fan-shaped stems: Stems are short and stout. As a plant matures, young leaves have difficulty emerging fully and this causes the stem to become flattened in cross-section and develop a fan-like appearance.

2.6.8.1.2 Problem Soils

Calcium deficiency is likely to occur in:

- Acidic, sandy soils whose original Ca has been removed by heavy rainfall
- Strongly acid peat and muck soils that have low total Ca

- Alkaline or sodic soils in which exchangeable Na and pH are high, thus depressing plant uptake of Ca
- Soil with high levels of soluble Al and low levels of exchangeable Ca

2.6.8.1.3 Correcting Deficiency

Calcium deficiency can be corrected by broadcasting suitable fertilizer onto the soil some months before sowing. Subsequent tillage operations then thoroughly mix the fertilizer with the soil. Where the chief problem is simply a lack of Ca, suitable fertilizers are gypsum (calcium sulfate) and calcium nitrate or chloride. If the soil pH is low, lime or limestone (calcium carbonate) and dolomite (a mixture of calcium and magnesium carbonates) are more suitable.

A soil test can determine soil lime or Ca requirement. However, since the correct rate of application depends on the soil type and crop to be grown, advice should be sought on fertilizer practices used on similar soils in the district. The excessive use of lime may induce deficiencies of K, Mg, Fe, Mn, Zn, and Cu, so care should be taken to prevent overliming.

2.6.8.2 Copper (Cu)

2.6.8.2.1 Deficiency Symptoms

The first signs of Cu deficiency may be areas of poor growth within an apparently healthy crop. Deficient plants appear limp and wilted even when ample water is available in the soil. If the deficiency persists and becomes severe, affected plants are shorter and develop thin, spindly stems and pale green to yellow foliage. When the deficiency is very severe, affected plants appear to die from the tops down, resulting in plants with dark green old leaves and crowns of dead leaves at the tops.

Copper deficiency affects the amount of live pollen formed. As a result, partly filled or even empty heads can be produced by plants that appear healthy. Heads without grain often turn white but remain firmly attached to the plants. A similar symptom is associated with frost, fungal, or mouse damage; the white heads are easily pulled from the stems in those situations.

Weather-tipped younger leaves: Because Cu is not readily transferred from old to young leaves when a deficiency occurs, symptoms develop first and are more severe on young leaves. Old leaves usually remain dark green and appear healthy. Affected leaves turn pale green to yellow and appear limp or wilted. If the deficiency persists, the tips of young leaves wilt, hang down, and turn yellow. The leaf tips eventually die and turn pale brown, rolling or twisting into tight tubes. The bases of the affected leaves may remain green when a deficiency is mild, but entire leaves are affected and die if a deficiency is very severe.

Increased tillering: In mild deficiencies, tiller production may be increased by the development of late tillers around the boot stage of growth. The new tillers are usually formed from nodes or joints that are well above ground level.

Delayed maturity and black straw: Copper deficiency delays crop maturity. When plants eventually ripen, their straw is usually much darker than normal and may be black or dark grey.

2.6.8.2.2 Problem Soils

Copper deficiency is likely to occur in:

- Peat and muck soils in which organic matter ties up soluble Cu in forms less available to plants
- Calcareous sands whose total Cu is low
- Leached acid soils whose total Cu is low
- Soils formed from rocks low in Cu

2.6.8.2.3 Correcting Deficiency

Foliar sprays and soil dressings of salts such as copper sulfate (bluestone) or copper chelates have corrected deficiencies. Dressings should be broadcast and mixed into the soil some weeks before

sowing. However, soil dressings may fail to correct the deficiency in some seasons and symptoms may reappear. If this occurs, foliar sprays should be applied immediately.

A reliable remedy is to apply two or more foliage sprays of 0.5 to 1% solutions of soluble Cu salts (for example, 0.5 to 1 kg copper sulfate per 100 L water per ha), the first to be applied 5 to 8 weeks after seedling emergence when the crop is in the tillering stage. The second spray is applied when the first or oldest heads reach the boot stage of growth; an optional third spray can be applied 7 to 10 days later.

Soil tests can estimate the amount of available Cu in a soil and predict the amount of fertilizer needed for most seasons. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

2.6.8.3 Iron (Fe)

2.6.8.3.1 Deficiency Symptoms

Iron-deficient plants are stunted and have short, spindly stems and pale green to yellow foliage. Because the symptoms are more severe on upper leaves, the crop has a distinct yellow color. Tiller production is reduced even by mild deficiencies. If a deficiency persists or becomes severe, many young tillers die without producing heads and mature tillers develop small heads. Grain yields can be severely reduced.

Interveinal chlorosis on younger leaves: Because Fe is not transferred from old to young leaves when a deficiency occurs, symptoms appear first and are more severe on young leaves. Old leaves usually remain dark green and appear healthy. During the early stages of symptom development, the youngest leaves turn pale green or yellow and the veins remain dark green and clearly visible. If the deficiency persists or becomes severe, the veins may lose their green color and the youngest leaves often turn dark or pale yellow, but rarely white. At this stage, it can be difficult to distinguish between S and Fe deficiencies, although Fe-deficient plants usually have a greener overall appearance than those deficient in S.

2.6.8.3.2 Problem Soils

Iron deficiency is likely to occur in:

- Calcareous soils whose levels of soluble Fe are low
- Waterlogged soils
- Acid soils with excessively high levels of soluble Mn, Zn, Cu, and Ni that depress plant uptake of Fe
- Sandy soils low in total Fe
- Peat and muck soils in which organic matter ties up Fe

2.6.8.3.3 Correcting Deficiency

While dressings of inorganic salts such as iron sulfates or chlorides have corrected deficiencies in some soils, the applied Fe quickly becomes insoluble and less available to plants. Fe salts of organic chelates have proved more promising because the chelate has the ability to keep Fe in solution in soils. For acid soils, FeEDTA is the most effective chelate. FeHEDTA and FeDTPA are best on neutral soils and FeEDDHA is best on alkaline, calcareous soils. However, to be effective, large amounts of chelates may be required and may prove too costly.

An equally effective remedy is to apply solutions of inorganic salts or chelates to the foliage (1% solution or 1 kg salt per 100 L water per ha). Because Fe is so immobile in plants, sprays may need to be applied every 10 to 15 days to provide Fe to new leaves. Advice on fertilizer practices used on similar soils in the district should be sought to obtain the best remedy for the affected crop under local conditions.

2.6.8.4 Magnesium (Mg)

2.6.8.4.1 Deficiency Symptoms

Magnesium-deficient wheat and triticale plants are stunted and have short, spindly stems and pale green to yellow foliage. Although tiller production may not be affected, many young tillers die before reaching maturity if a deficiency persists or becomes severe. Extremely deficient plants develop only a few heads that set few grains.

Interveinal chlorosis on older leaves: Because Mg is readily transferred from old to young leaves when a deficiency occurs, symptoms appear first and are more severe on old leaves, working up the plants to younger leaves as the deficiency develops. Pale yellow interveinal chlorosis begins between the leaf tips and the mid-sections of middle and old leaves and rapidly expands toward the bases until whole leaves are affected. During early stages, the veins remain green and prominent. As the deficiency becomes more severe, the veins become less distinct and the interveinal tissue may die and turn pale or dark brown. Necrosis of interveinal tissue is more common on old leaves and usually occurs toward the tips. The youngest leaves remain green and appear healthy.

2.6.8.4.2 Problem Soils

Magnesium deficiency is likely to occur in:

- Acid sandy soils whose Mg has been removed by leaching
- Strongly acid peat and muck soils whose total Mg is low
- Soils that have been over-fertilized with Ca (for example, lime) or K, thus inhibiting uptake of Mg

2.6.8.4.3 Correcting Deficiency

Magnesium deficiency on acid soils is best corrected by broadcasting dolomite (a mixture of calcium and magnesium carbonates) onto the surface some months before sowing. The dolomite is then mixed thoroughly with the topsoil during seedbed preparation. When the problem is simply a deficiency of Mg, applications of magnesium sulfate or chloride can be made at or before planting.

A soil test can estimate the amounts of soluble and exchangeable Mg in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Magnesium deficiency in existing crops can be corrected by applying soluble salts such as magnesium sulfate, chloride, or nitrate with irrigation water. Foliar sprays of soluble magnesium salts such as magnesium sulfate are usually not recommended because of the large number of applications required to supply crop requirements.

2.6.8.5 Manganese (Mn)

2.6.8.5.1 Deficiency Symptoms

Manganese-deficient crops often appear patchy and exhibit areas of poorer growth adjacent to apparently healthy plants. Within the Mn-poor area, plants are stunted and have short, thin, spindly stems and pale green to yellow foliage. Affected plants often have wilted appearance and prostrate growth. Even mild deficiencies cause plants to produce few tillers. When a deficiency is severe, many young tillers and sometimes whole plants die before maturity. As a result, grain yields may be greatly reduced.

White flecks in younger leaves: Because Mn is not readily transferred from old to young leaves when a deficiency occurs, symptoms develop first and are more severe on young leaves. When the deficiency persists, the severest symptoms appear on the youngest leaves. The oldest leaves may show mild symptoms. Affected leaves turn pale green and appear limp or wilted. Mild interveinal chlorosis develops in the mid-sections of leaves and spreads rapidly. Whole leaves turn pale yellow-green. Small, linear grey to white flecks or streaks appear in interveinal tissues toward the bases.

Wilted leaves: If the deficiency persists or becomes severe, the leaves bend downward and lie on the surface of the soil and the plants appear wilted. This is caused by joining of the white flecks at the bases of the leaves. The basal tissue then dies and turns pale brown. Initially, the leaf tips remain green and appear healthy but eventually whole leaves die.

Deaths of shoots: Severe deficiency causes the youngest leaves to die before they emerge fully from the sheaths of the previous leaves. When this occurs, the apical microstem soon dies and then the whole shoot dies.

2.6.8.5.2 Problem Soils

Manganese deficiency is likely to occur in:

- Calcareous soils whose Mn is less available to plants
- Poorly drained soils with high organic matter content in which Mn is tied up in forms less available to plants
- Strongly acid sandy soils whose soluble Mn has been leached by heavy rain
- Soils formed from rocks low in Mn

2.6.8.5.3 Correcting Deficiency

Foliar sprays and soil dressings of Mn salts and oxides have been used to correct deficiencies. Soil dressings are more effective when broadcast and mixed into the soil some weeks before sowing. Foliar applications have generally been more successful. One or more sprays of 0.5 to 1% solutions of soluble Mn salts (for example, 0.5 to 1 kg manganese sulfate per 100 L water per ha) usually correct the deficiency, the first to be applied 5 to 6 weeks after seedling emergence. If symptoms reappear, the spray should be repeated immediately. While soil dressings usually last 5 to 6 years, foliar sprays must be reapplied to every crop.

Tests can estimate the amount of available Mn in the soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

2.6.8.6 Nitrogen (N)

2.6.8.6.1 Deficiency Symptoms

Nitrogen deficiency leads to stunted plants with thin, spindly stems and short, erect leaves. In young crops, all leaves are pale green to yellow. Mature crops often take on a three-tone appearance: the oldest leaves are pale lemon yellow or pale brown; the middle leaves are yellow; and the youngest are pale green. Tiller production is reduced and if the deficiency is severe, many die before maturing, forming thatches of dead leaves around the bases of the plants. Grain yields are severely reduced.

Mottled grain: An early warning sign is the production of low protein grain. In bread wheats, such grain is only partly vitreous and has opaque patches or mottles.

Pale yellow older leaves: Because N is readily transferred from old to young leaves as soil supplies become deficient, symptoms appear first and are more severe on old leaves, working up the plants to younger leaves if the deficiency persists. The youngest leaves remain pale to dark green and appear healthy but may be short and more erect than usual. Old leaves turn pale green. Pale yellow chlorosis develops at the leaf tips and advances in broad fronts down the leaves. The chlorotic tissues die and turn pale brown. Affected leaves can be green at the bases and develop yellow mid-sections and brown leaf tips.

Red stems: Deficient plants usually have green, thin, spindly stems. However, in cold weather, stems, leaf sheaths and auricles may develop red stripes, a symptom usually associated with P deficiency.

2.6.8.6.2 Problem Soils

Nitrogen deficiency is likely to occur in:

- Sandy soils that have been leached by heavy rainfall or excessive irrigation
- Mineral soils low in organic matter
- Soils with a long history of cropping, where the supplies of N are exhausted

Even fertile soils may suffer temporary N deficiency when double-cropped, heavily leached or waterlogged.

2.6.8.6.3 Correcting Deficiency

Nitrogen deficiency is corrected by increasing the available N in the soil by fallowing, which allows organic N to be converted to mineral N; by growing cover or cash crops of legumes, which can fix atmospheric N_2; or by adding nitrogenous fertilizers. Suitable fertilizers are urea, gaseous ammonia or ammonium sulfate, nitrate, or phosphates. Crop growth depends on the amount of N already in the soil. A soil test can measure the amount of total N or (NO_3)-N in the soil prior to sowing, and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Nitrogen deficiency in existing crops is sometimes corrected by applying soluble salts such as urea with irrigation water or as a foliar spray. Spray applications usually result in a rapid response of short duration, and additional sprays 10 to 14 days apart may be needed to supply enough N for crop requirements.

2.6.8.7 Phosphorus (P)

2.6.8.7.1 Deficiency Symptoms

Symptoms are more noticeable in young plants, which have greater relative demands for P than more mature plants. Mild deficiencies cause stunted growth but no obvious leaf symptoms. More severe deficiencies produce small, dark green plants that have short, erect leaves, stout stems, and often develop orange, red, or purple areas. Tiller production and grain yield are reduced even by mild deficiencies. When a deficiency persists or becomes severe, little grain is produced because many young tillers die before maturity and the surviving tillers produce small heads that set few grains.

Dark yellow older leaves: Because P is readily transferred from old to young leaves when a deficiency occurs, symptoms develop first and are more severe on old leaves, working up the plants to younger leaves if the deficiency persists. The youngest leaves remain dark green and appear healthy but may be short and more erect than usual. Old leaves remain dark green and dark yellow chlorosis develops on the leaf tips and advances in broad fronts down the leaves. If the deficiency is severe or persists, purple suffusion combines with the yellow to produce orange-yellow to orange-purple chlorosis. Eventually the affected leaves die, turn dark brown, and form thatches around the bases of the plants.

Purple stems: Red-purple or purple striping develops on stems and leaf sheaths even when a deficiency is mild.

2.6.8.7.2 Problem Soils

Phosphorus deficiency is likely to occur in:

- Mineral soils low in organic matter
- Soils with a long history of cropping, whose supplies of P are depleted
- Highly weathered, Fe-rich acid soils whose phosphate is fixed in less available forms
- Soils whose P-rich topsoil has been lost through erosion
- Alkaline soils in which much of the P may be tied up in insoluble phosphates that are less available to plants

2.6.8.7.3 Correcting Deficiency

Phosphorus deficiency can be corrected by applying phosphatic fertilizers at or before sowing. Suitable fertilizers are single or triple superphosphates or ammonium phosphates. Crop growth depends on the amounts of water-soluble phosphates and the rates of exchange between insoluble and soluble forms of P in the soil. Soil tests can estimate the amounts of available phosphate in soils and predict the amounts of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Phosphorus deficiency in existing crops can be corrected by applying soluble salts such as ammonium phosphates with irrigation water. Spray applications of similar salts are usually not recommended because of the large number required to supply enough P.

2.6.8.8 Potassium (K)

2.6.8.8.1 Deficiency Symptoms

Deficient plants are stunted and have thin, spindly stems and pale green, yellow-tipped foliage. The lower leaves may wilt and lie on the surface of the soil or may die and turn brown if the deficiency is severe. Tiller production is usually not affected by mild deficiency. However, if it persists or becomes severe, many young tillers die before producing heads, while mature tillers produce small heads that set few grains.

Marginal yellowing on older leaves: Because K is readily transferred from old to young leaves when a deficiency occurs, symptoms appear first and are more severe on old leaves, working up the plants to younger leaves if the deficiency persists. The youngest leaves usually remain green and appear healthy. On old leaves, symptoms appear on the tips and advance along the margins toward the bases, usually leaving the mid-veins alive and green. The symptoms become clearly recognizable only when a deficiency is severe. In mild deficiencies, leaves may be pale green and appear limp or wilted and lack other signs of disorder. When a deficiency is severe, the tips and margins of older leaves become bright yellow or dull yellow-brown. Eventually the affected tissue dies and turns dark brown, giving the leaf margins a ragged appearance.

2.6.8.8.2 Problem Soils

Potassium deficiency is likely to occur in:

- Mineral soils low in organic matter after many years of cropping
- Sandy soils formed from parent material low in K
- Light textured soils whose original K has been leached by rainfall

2.6.8.8.3 Correcting Deficiency

Potassium deficiency is corrected by applying potassium nitrate, sulfate, or chloride to the soil at or before sowing. Crop yield depends on the amounts of water-soluble and exchangeable K in the soil. Tests can estimate the amount of available K in the soil and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Potassium deficiency in existing crops can be corrected by applying soluble K salts such as potassium sulfate, chloride, or nitrate with irrigation water. The foliar application of similar salts is usually not recommended because of the large number of sprays needed to supply crop requirements.

2.6.8.9 Sulfur (S)

2.6.8.9.1 Deficiency Symptoms

Sulfur deficiency causes stunted growth, delayed maturity, and yellowing of leaves. In young crops or when the deficiency is mild, stunting is limited. The first symptom of a deficiency is general yellowing over the whole plant followed by severe symptoms developing on upper leaves. In the

early stages, upper leaves turn pale green to yellow while lower leaves remain green. If the deficiency persists and becomes severe, upper leaves turn pale yellow to white and lower leaves turn pale green. The yellowing is not confined to areas between the veins and affects entire leaves. Leaf tissue usually does not die even when the leaves have turned white.

2.6.8.9.2 Problem Soils

Sulfur deficiency is likely to occur in:

- Mineral soils low in organic matter after many years of cropping
- Soils formed from parent material low in S (for example, some volcanic rocks and ash)
- Acid sandy soils whose original sulfates have been removed by leaching

2.6.8.9.3 Correcting Deficiency

Soil dressings of any S fertilizer will correct deficiencies. Elemental S (flowers of sulfur) can be broadcast and thoroughly mixed into the soil about 4 months before sowing. Gypsum (calcium sulfate) is another useful source of S.

In soils not subject to heavy leaching, tests can estimate the amount of available sulfate before sowing and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Sulfur deficiency in existing crops can be corrected by applying soluble sulfate salts such as magnesium, ammonium, or potassium sulfate in irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to supply crop requirements.

2.6.8.10 Zinc

2.6.8.10.1 Deficiency Symptoms

Zinc-deficient crops often appear patchy, with deficient plants adjacent to well grown, apparently healthy plants. Deficient plants are stunted and have short, thin stems and usually pale green foliage. If the deficiency continues and becomes severe, plants cease growth and often develop a grass-tufted appearance. Tiller production is usually normal in mild deficiencies but many young tiers die without developing heads if the deficiency persists. When it is severe, tillering is greatly reduced and the few heads produced may have little or no grain.

Chlorosis and necrosis of middle leaves: Zinc is partly mobile in wheat and triticale and the first symptoms originate halfway up the middle leaves. The youngest leaves at the top and the oldest at the base of the shoots may be unaffected initially, but will develop symptoms if the deficiency persists. Symptoms appear in the lower halves of the leaves, commencing as yellow chlorotic areas between the mid-veins and leaf margins and extending outward toward the tips and bases. These chlorotic areas eventually die and turn pale grey or brown. The affected areas may remain discrete, producing separate, linear brown or grey lesions or they may join, involve the mid-veins, and result in the deaths of the central areas of the leaves, leaving the tips, bases, and margins green.

Chlorotic and necrotic lesions on the leaf sheath: Similar chlorotic areas and grey lesions may develop on the leaf sheaths when a deficiency is severe.

2.6.8.10.2 Problem Soils

Zinc deficiency is likely to occur in:

- Strongly alkaline soils whose availability of Zn is depressed
- Leached sandy soils whose total Zn is low
- Leveled soils whose Zn-deficient subsoils may be exposed on the surface
- Soils in which heavy, frequent applications of phosphatic fertilizers may have reduced crop use of Zn

2.6.8.10.3 Correcting Deficiency

Foliar and soil applications of Zn salts have been used to correct deficiencies. Soil dressings of zinc chelates, sulfates or oxides should be broadcast and mixed into soil 2 to 3 months before sowing. While soil dressings usually remain effective for 6 to 8 years before more are needed, foliar sprays have no residual effects and fresh applications must be made to each crop. Best results are obtained when two sprays of a 0.5 to 1% solution of a soluble Zn salt such as zinc sulfate heptahydrate (0.5 to 1 kg Zn salt per 100 L water per ha) are applied about 2 weeks apart, the first applied 2 to 3 weeks after seedling emergence.

Soil tests estimate the amount of available Zn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

2.6.9 Salinity[2]

2.6.9.1 Saline Toxicity

TABLE 2.107
Effects of Salinity on Wheat

Appearance	Causal Factors
Unthrifty, low-yielding crops	Excessive NaCl leads to short, stunted plants that have generally short, erect leaves. Affected plants have a harsh, droughty appearance, short, spindly stems, and bluish-green foliage. Young plants may appear only droughted. Older leaves of more mature plants may be brown and dead and lie on the soil surface around the bases of the plants. Tiller production may not be affected but if the toxicity persists, many young tillers die before maturity. On mature tillers, heads are small and set few grains.
Dull yellow leaf tips on older leaves	The leaf tips of old leaves turn dull yellow due to the accumulation of excess NaCl in tissues that transpired the greatest amounts of water during the life of the plant. Symptoms appear first and are more severe on the oldest leaves, working up the plants to younger leaves as the toxicity persists. The leaves are shorter than normal and appear harsh and wilted. They are carried erect and are dark green or dull bluish-green. The tips of the oldest leaves turn dull, dark yellow then die and turn pale brown. As the toxicity worsens, the chlorosis and necrosis advance down the leaves, usually along the margins, until entire leaves die.
Red-purple awns	In awned wheats, the glumes and awns may develop reddish-purple areas.

2.6.9.2 Problem Soils

Sodium chloride toxicity is more likely to occur in:

- Saline soils formed from salt water sediments
- Previously fertile soils that were flooded or heavily irrigated with water containing high concentrations of NaCl

2.6.9.3 Correcting Toxicity

Leaching with good quality irrigation water is the most effective means of removing excess Na and Cl from the soil. The water table may have to be lowered. Permeable soils such as well structured sandy soils are often easily reclaimed, but the problem is more difficult in less permeable soils (for example, poorly structured heavy clays).

If exchangeable Na in the soil is high, reclamation involves replacing the adsorbed Na with Ca by applying gypsum (calcium sulfate) and then leaching the dissolved Na and Cl beyond the rooting depths of the plants. If irrigation water is to be used to leach the Na, the quality of the water should be checked before use to make sure it is not saline. Where excess NaCl cannot be wholly corrected by leaching, a more tolerant species may have to be grown.

2.6.10 Weights and Measures

A bushel of wheat grain weighs 60 lb (27.2 kg).

TABLE 2.108
Wheat Seeds/Pound, Weight/Bushel, and Germination Time

Seeds/lb (1,000)	Seeds/g (no.)	Weight/bu (lb)	Germination time (days)
12–20	35	60	7

TABLE 2.109
Weight and Standard Yield of Level Full Bushel of Wheat Grain

Weight of 1 Measured Bushel (lb)	Multiplication Factor to Yield Standard Bushel
64	1.07
62	1.03
60	1.00
58	0.97
56	0.93
54	0.90
52	0.87
50	0.83
48	0.80
46	0.77
44	0.73
42	0.70
40	0.67

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3 Nut, Bean, and Oil Crops

3.1 PEANUT OR GROUNDNUT (*Arachis hypogaea* L.)

3.1.1 Introduction

The peanut plant belongs to the pea or Leguminosae family and is known as arachide in France, mani or cacahuete in Spain, pistacchio di terra in Italy, erdnuss in Germany, and amendoim in Portugal. The plant is a native of South America. Indians grew peanuts at least 1,000 years ago, although farmers in Africa and Asia now grow about 90% of the world total. The leading peanut-growing countries are India, China, and the U.S. Georgia produces about half the annual U.S. peanut crop. Since the pods develop underground, peanuts are often called groundnuts, and are also called goobers. They are nutritious; peanuts and peanut butter contain more energy-providing calories than equal weights of beefsteak.

About one half the peanuts consumed in the U.S. are in the form of peanut butter and about one fourth are consumed as roasted nuts. Peanut oil has both food (cooking and salad oils and dressings, margarine, and other vegetable shortenings) and industrial uses (as an ingredient in soap, face powders, shaving creams, shampoos, paints, and explosives). It is undergoing testing as a fuel source. The meal remaining after the oil is extracted is used as a protein animal feed and the protein in the meal used to make a textile fiber. Powdered peanut shells are used to make plastics, cork substitutes, wallboard, and abrasives. About 60% of the world's peanut production is used to produce oil. Worldwide peanut oilseed production represents 10% of all oilseeds — a total of 31.6 million short tons.

Peanut plants grow best in well-drained sandy soils and sunny warm temperatures (4 to 5 frost-free months) with moderate rainfall. The plant is a legume that can meet its nitrogen (N) requirement by bacterial symbiotic nitrogen (N_2) fixation. The average yield in the U.S. in the year 2000 was 2,499 lb per acre.

3.1.2 Stages of Growth

TABLE 3.1
Peanut Growth Stages

Stage[a]	Abbreviated Title	Description
V-E	Emergence	Cotyledons near the soil surface with some part of the seedling plant visible
V-O	—	Cotyledons are flat and open at or below the soil surface
V-1	First tetrafoliate	One node on the main axis with its tetrafoliolate leaflets unfolded and flat
V-n	Additional V stages	n developed nodes on the main axis; a tetrafoliolate node is counted when its leaflets are unfolded and flat
R-1	Beginning bloom	One open flower at any node on the plant
R-2	Beginning peg	One elongated peg
R-3	Beginning pod	One peg in the soil with turned, swollen ovary at least twice the width of the peg
R-4	Full pod	One fully-expanded pod; size characteristic of the cultivar
R-5	Beginning seed	One fully-expanded pod in which seed cotyledon growth is visible when the fruit is cut in cross-section
R-6	Full seed	One pod with seed cavity apparently filled
R-7	Beginning maturity	One pod showing visible, natural coloration or blotching of inner pericarp or testa
R-8	Harvest maturity	2/3 to 3/4 of all developed pods have testa or pericarp coloration; fraction is cultivar-dependent, lower for Virginia types
R-9	Over-mature pod	One undamaged pod showing orange-tan coloration of the testa and/or natural peg deterioration

[a] Vegetative (V) and reproductive (R) stages are considered established when at least 50% of the plants in the sample reach that stage. The establishment of the R Stage for an individual plant is based on the first occurrence of the specific trait without regard to position on the plant.

Source: *Crop Production: Evolution, History, and Technology*, 1995, John Wiley & Sons, New York.

3.1.3 Production Statistics

TABLE 3.2
U.S. Peanut Acreage, Yield, and Production, 1991–2000

Year	Harvested Area (1,000 acres)	Yield (lb/acre)	Production (1,000 lb)
1991	2,015.7	2,444	4,926,570
1992	1,669.1	2,567	4,284,416
1993	1,689.6	2,008	3,392,415
1994	1,616.5	2,624	4,247,455
1995	1,517.0	2,282	3,461,475
1996	1,380.0	2,653	3,661,205
1997	1,413.6	2,503	3,539,360
1998	1,467.0	2,702	3,963,440
1999	1,436.0	2,667	3,629,490
2000[a]	1,315.5	2,499	3,287,600

[a] Preliminary.

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 3.3
Peanut Acreage, Yield, and Production by State, 2000

State	Area Harvested (1,000 acres)	Yield (lb/acre)	Production (1,000 lb)
Alabama	192	1,420	272,640
Florida	86	2,385	205,110
Georgia	487	2,750	1,339,250
New Mexico	24	2,500	60,000
North Carolina	123	2,900	356,700
Oklahoma	67	1,950	130,650
South Carolina	11.5	3,000	34,500
Texas	250	2,700	675,000
Virginia	75	2,800	213,750

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 3.4
Peanuts in the Shell: Area, Yield, and Production by Continent, 1999–2000

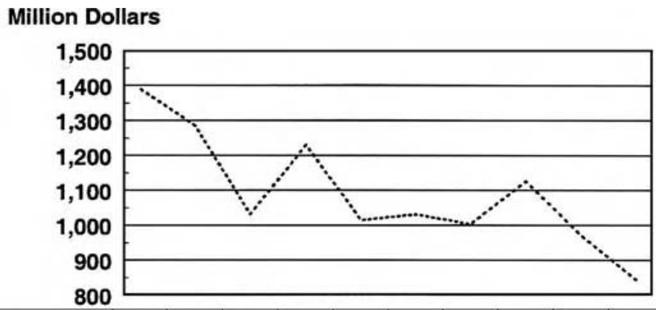
Continent	Area (1,000 ha)	Yield (metric tons/ha)	Production (1,000 metric tons)
North America	675	2.77	1,872
South America	305	1.89	575
Africa	6,429	0.91	5,865
Asia	14,109	1.46	20,639
World Total	21,602	1.35	29,149

Source: Foreign Agriculture Service, Washington, D.C.

TABLE 3.5
Peanuts in the Shell: Area, Yield, and Production in Specified Countries, 1999–2000

Country	Area (1,000 ha)	Yield (metric tons/ha)	Production (1,000 metric tons)
India	8,000	0.69	5,500
China	4,268	2.96	12,639
Nigeria	1,200	1.21	1,450
Indonesia	650	1.52	990
U.S.	581	2.99	1,737
Sudan	550	0.67	370
Zaire	545	0.76	415
Myanmar	490	1.15	562
World Total	21,602	1.35	29,149

Source: Foreign Agriculture Service, Washington, D.C.



Year	91	92	93	94	95	96	97	98	99	00
Value of Prod:···	1,392	1,285	1,031	1,229	1,013	1,030	1,003	1,126	972	845

FIGURE 3.1 Peanuts: Value of U.S. production, 1991–2000.

3.1.4 Nut Quality

TABLE 3.6
Nutritive Value of Whole Peanut Seed

Component	Level
Calories/100 g	564
Protein,%	26.0
Fat,%	47.5
Total calcium, mg/lb	69
Total phosphorus, mg/lb	401
Total potassium, mg/lb	674
Carbohydrates,%	18.6

TABLE 3.7
Nutritive Value of Raw Peanut with Skin

Component	Level (%)
Fat	47.5
Protein	26.0
Carbohydrate	18.6
Water	5.6
Other	2.3

Source: *Composition of Foods*, 1961, Agricultural Handbook No. 8, U.S. Department of Agriculture, Washington, D.C.

3.1.5 Nutrient Element Uptake

TABLE 3.8
Uptake of Major Elements and Micronutrients for a 4.5-Ton/Acre Peanut Crop

Major Elements (kg)	
Nitrogen	270
Phosphorus as phosphate	45
Potassium as potash	92
Calcium	20
Magnesium	25
Sulfur	21
Micronutrients (g)	
Copper	60
Iron	480
Manganese	400

Source: International Soil Fertility Manual. 1995. Potash & Phosphate Institute, Norcross, GA. With permission.

3.1.6 Standards and Grades[1]

3.1.6.1 Farmers' Stock Virginia Type

U.S. No. 1 Unshelled Virginia-type peanuts that are mature, dry, and practically free from foreign material. Not less than 45% by weight of any lot shall consist of jumbo and fancy hand-picks and of this amount not less than 3/4 or 34% of the total unshelled weight shall be jumbo handpicks.

U.S. No. 2 Unshelled Virginia-type peanuts that are mature, dry, and practically free from foreign material. Not less than 35% by weight of any lot shall consist of jumbo and fancy hand-picks and of this amount not less than 3/5 or 21% of the total unshelled weight shall be jumbo hand-picks.

U.S. No. 3 Unshelled Virginia-type peanuts that are mature, dry, and practically free from foreign material.

Unclassified Unshelled Virginia-type peanuts that do not meet the requirements of the foregoing grades.

Large kernels Peanuts pass over a screen having 20/64- by 1-in. perforations.

Medium kernels Peanuts that will pass through a screen having 20/64- by 1-in. perforations and over a screen having 15/64- by 1-in. perforations.

Small kernels Peanuts that will pass through a screen having 15/64- by 1-in. perforations. *Note:* The large, medium, and small kernel terms are equivalent to extra large No. 1 and No. 2 terms now commonly used to designate kernels. The large, medium, and small descriptions are cited here to avoid confusion with the U.S. No. 1, U.S. No. 2, etc. grades that deal with hand-picks, shelled, and defective peanuts.

3.1.6.2 Farmers' Stock Runner Type

U.S. No. 1 Unshelled runner peanuts that are mature, dry, and practically free from damage. When shelled, the sound and mature kernels shall not be less than 65% of the total weight of the sample.

U.S. No. 2 Unshelled runner peanuts that are mature, dry, and practically free from damage. When shelled, the sound and mature kernels shall not be less than 60% of the total weight of the sample.

U.S. No. 3 Unshelled runner peanuts that are mature, dry, and practically free from damage. When shelled, the sound and mature kernels shall not be less than 55% of the total weight of the sample.

U.S. sample grade Unshelled runner peanuts that do not meet any of the foregoing grades.

Sample Total quantity of material taken for examination including all shelled and unshelled stock and foreign material.

Practically free from damage Relates to shelled peanuts. No appreciable amount of nuts with cracked shells shall be noticeable.

Damaged kernels

1. Kernels that are rancid or decayed.
2. Moldy kernels.
3. Kernels showing sprouts over 1/8 in. long; all sprouted kernels, the separated halves of which show decay, shall be classed as damaged.
4. Dirty kernels; surfaces are distinctly dirty and the dirt is ground in.
5. Wormy or worm-injured kernels.
6. Kernels that show yellow discoloration when the skin is removed.
7. Kernels having skins that show dark brown discoloration, usually netted and irregular, and affecting more than 25% of the skin; kernels having skins that are paler or darker than characteristic of the variety that are not actually discolored shall not be classed as damaged.

Mature Kernels are fully developed.

Hand-picks Unshelled peanuts that are clean, fairly bright, mature, dry, and free from mildewed or speckled shells, paper ends, and cracked or broken shells. Hand-picks shall not pass through a slotted screen having 32/64- by 3-in. perforations.

Fancy hand-picks Hand-picks that will pass through a slotted screen having 37/63- by 3-in. perforations, but will not pass through a screen having 32/64- by 3-in. perforations.

Jumbo hand-picks Hand-picks that will not pass through a slotted screen having 37/64- by 3-in. perforations.

3.1.6.3 Shelled Spanish Type

U.S. No. 1 Spanish Shelled Spanish peanut kernels of similar varietal characteristics that are whole and free from foreign material, damage, and minor defects, and will not pass through a screen having 15/64- by 3/4-in. openings.

U.S. Spanish splits Shelled Spanish-type peanut kernels of similar varietal characteristics that are split or broken, but free from foreign material, damage, and minor defects, and will not pass through a screen having 16/64-in. round openings.

U.S. No. 2 Spanish Shelled Spanish peanut kernels of similar varietal characteristics that may be split or broken, but free from foreign material, damage, and minor defects, and will not pass through a screen having 16/64-in. round openings.

3.1.6.4 Shelled Virginia Type

U.S. extra large Virginia Shelled Virginia-type peanut kernels of similar varietal characteristics that are whole and free from foreign material, damage, and minor defects, and will not pass through a screen having 20/64- by 1-in. openings. Unless otherwise specified, the peanuts in a lot shall average not more than 512 per lb.

U.S. medium Virginia Shelled Virginia peanut kernels of similar varietal characteristics but are whole and free from foreign material, damage, and minor defects, and will not pass through a screen having 18/64- by 1-in. openings. Unless otherwise specified, the peanuts in a lot shall average not more than 640 per lb.

U.S. No. 1 Virginia Shelled Virginia peanut kernels of similar varietal characteristics that are whole and free from foreign material, damage, and minor defects, and will not pass through a screen having 15/64- by 1-in. openings. Unless otherwise specified, the peanuts in a lot shall average not more than 864 per lb.

U.S. Virginia splits Shelled Virginia-type peanut kernels of similar varietal characteristics that are free from foreign material, damage, and minor defects, and will not pass through a screen having 20/64-in. round openings. Not less than 90% by weight shall be splits.

U.S. No. 2 Virginia Shelled Virginia-type peanut kernels of similar varietal characteristics that may be split or broken but are free from foreign material, damage, and minor defects, and will not pass through a screen having 17/64- by 1-in. round openings.

3.1.6.5 Shelled Runner-Type

U.S. No. 1 runners Shelled runner-type peanut kernels of similar varietal characteristics that are whole and free from foreign material, damage, and minor defects, and will not pass through a screen having 16/64- by 3/4-in. openings.

U.S. runner splits Shelled runner peanut kernels of similar varietal characteristics that are slit or broken, but are free from foreign material, damage, and minor defects, and will not pass through a screen having 17/64-in. round openings.

U.S. No. 2 runners Shelled runner-type peanut kernels of similar varietal characteristics that may be split or broken, but are free from foreign material, damage, and minor defects, and which will not pass through a screen having 17/64-in. round openings.

Similar varietal characteristics Peanut kernels in a lot are not of distinctly different varieties. For example, Spanish types are not mixed with runners.

Whole A peanut kernel is not split or broken.

Split Separated half of a peanut kernel.

Broken More than 1/4 of the peanut kernel is broken off.

Foreign material Pieces or loose particles of any substance other than peanut kernels or skins.

Unshelled A peanut kernel with part or all of the hull (shell) attached.

Minor defect A peanut kernel is not damaged but is affected by one or more of the following: (1) dark brown, dark gray, dark blue, or black skin discoloration that covers more than 1/4 of the surface; (2) flesh discoloration that is darker than light yellow or consists of more than slight yellow pitting of the flesh; (3) a sprout extending more than 1/8 in. from the tip of the kernel; and (4) the surface of the kernel is distinctly dirty, and its appearance is materially affected.

Damage A peanut kernel is affected by one or more of the following: (1) rancidity or decay; (2) mold; (3) insects, worm cuts, web, or frass; (4) freezing injury causing hard, translucent, or discolored flesh; and (5) the surface of the kernel is heavily smeared, thickly flecked, or coated with dirt and its appearance is seriously affected.

3.1.6.6 Cleaned Virginia Type

U.S. jumbo hand-picked Cleaned Virginia-type peanuts in the shell that are *mature*, dry and free from loose peanut kernels, dirt, or other foreign material, *pops*, *paper ends*, and *damage* caused by *cracked or broken shells*, *discoloration*, or other means. The kernels shall be free from damage (*rancidity*, *decay*, *mold*, *sprouts*, *dirt*, *worms*, *discoloration*) from any cause. The peanuts shall not pass through a screen having 37/64- by 3-in. perforations. Unless otherwise specified, the unshelled peanuts in any lot shall not average more than 176 *count per lb*. [***Note:*** Italicized terms are explained in the *Other Terms* section below.]

U.S. fancy hand-picked Cleaned Virginia peanuts in the shells meeting the same standards as U.S. jumbo hand-picks, except the peanuts shall not pass through a screen having 32/64- by 3-in. perforations. Unless otherwise specified, the unshelled peanuts in a lot shall not average more than 225 per lb.

Unclassified Cleaned Virginia-type peanuts in the shell that fail to meet the requirements of the foregoing grades. "Unclassified" is not a grade within the meaning of these standards. It is provided as a designation to show that no definite grade is appolied to a lot.

Other terms *Mature:* Shells are firm and well developed.

Pops: Fully developed shells that contain practically no kernels

Paper ends: Peanut shells that have very soft and/or very thin ends

Damage: An injury or defect that materially affects the appearance, edibility, or shipping quality of an individual peanut or a lot as a whole. The following shall be considered damages:

1. Cracked or broken shells are broken to the extent that kernels within the shells are plainly visible without minute examination and with no application of pressure, or where the appearance of individual peanuts are materially affected.
2. Discolored shells that have dark discoloration caused by mildew, staining, or other means affecting half or more of the shell surtace. Talc powder or other similar material that may have been applied to the shells during the cleaning process shall not be removed to determine the amount of discoloration beneath, but the peanut shall be judged as it appears with the talc.
3. Rancid or decayed kernels.
4. Moldy kernels.
5. Kernels showing sprouts extending more than 1/8 in. from the ends of the kernels.
6. Distinctly dirty kernels.
7. Kernels that are wormy, have worm frass adhering, or have worm cuts that are more than superficial.
8. Kernels that have dark yellow color penetrating the flesh or yellow pitting extending deep into the kernels.

Count per pound: Number of peanuts in a pound. When determining count per pound, a single-kernel peanut shall be counted as 1/2 peanut.

TABLE 3.9
Allowable Percentages for Farmers' Stock Runners Based on Total Weight of Sample

Grade	Tolerance for Other Varieties	Tolerance for Sound Kernels	Tolerance for Damaged Kernels
U.S. No. 1	1	65	2
	66 +	3	
U.S. No. 2	1	60	2
	61	3	
	62	4	
	63 +	5	
U.S. No. 3	1	55	2
	56	3	
	57	4	
	56	5	
	59 +	6	

Source: U.S. Department of Agriculture Federal Grain Inspection Service, Washington, D.C., 1983.

3.1.7 Weights and Measures

One pound of shelled nuts is equivalent to 1.5 lb unshelled nuts.

TABLE 3.10
Weights and Measures for Unshelled Peanuts

	Approximate Net Weight		
Commodity	Unit	lb	kg
Virginia	bushel	17	7.7
Runner	bushel	21	9.5
Spanish	bushel	25	11.3

Source: U.S. Department of Agriculture, *Agricultural Statistics, 2001*, U.S. Government Printing Office, Washington, D.C.

TABLE 3.11
Peanut Seeds/Pound, Weight/bu, and Germination Time

Seeds/lb (1,000)	Seeds/g (no.)	Weight/bu (lb)	Germination Time (days)
1	1–3	20–30	10

REFERENCES

1. Smith, C.W., *Crop Production: Evolution, History, and Technology*, 1995, John Wiley & Sons, New York.

3.2 SOYBEAN [*Glycine max* (L.) Merr.]

3.2.1 Introduction

Soybeans belong to the Fabaceae or Leguminosae pea family. The soybean is known as soya in French, soja in Spanish and Italian, and sojaböhne in German. Soybean culture dates back to 2,500 B.C. The plant is native to eastern Asia, Australia, and several Pacific Islands and is also called Chinese pea, Manchurian bean, Japan pea, Japan bean, and Japanese fodder plant.

The soybean was introduced to Europe in the early 1700s and to North America in 1765. It was grown as a forage crop in the U.S. until World War II. The acreage harvested for seed (beans) by 1930 was less than 25% of total acres planted; it increased to 40% by 1939. By 1944, the acreage harvested for the beans had increased to 74%. Today, most plants are harvested for their beans to be used primarily for meal and oil. In 1999, 171 million short tons of soybean oil were produced and represented 52% of all vegetable oil produced.

Soybean adapts to a wide range of climatic conditions, but is very susceptible to drought damage during flowering and grain filling.

The U.S. is the leading soybean-growing country (72.7 million acres in 2000). It provides about two-thirds of the world's soybeans, followed by China, India, and Indonesia. Other major soybean-growing countries are Nigeria, Russia, North Korea, Italy, and Thailand. In 1983, the highest verifiable soybean grain yield of 118 bu per acre was recorded in New Jersey. The U.S. average yield in 2000 was 38.1 bu per acre.

Soybean oil contains no cholesterol and has one of lowest levels of saturated fat among vegetable oils. The soy foods business in the United States is a $2.5 billion industry and growing. The products are soy milks, cheeses, and yogurts as dairy subsitutes, soy butter, corn dogs, and soyburgers. They require 6.5 million bu of soybeans and the number is projected to rise to 12.29 million bu by 2010. Speciality items, such as infant formula, nutritional supplements and bars, beverages and nutraceuticals or functional foods use 12.4 million bu and are projected to require 50 million bu by 2010.

3.2.2 Vegetative and Productive Stages

TABLE 3.12
Vegetative Stages

Stage	Abbreviated Title	Description
VE	Emergence	Cotyledons above the soil surface
VC	Cotyledon	Unifoliolate leaves unrolled sufficiently so the leaf edges do not touch.
V1	First node	Fully developed leaves at unifoliolate nodes
V2	Second node	Fully developed trifoliolate leaf at node above unifoliolate nodes
V3	Third node	Three nodes on the main stem with fully developed leaves beginning with the unifoliolate nodes
V(n)	nth node	Number of nodes on the main stem with fully developed leaves beginning with the unifoliolate nodes; *n* can be any number beginning with 1 for V1, first node stage

Source: *Stages of Soybean Development,* Iowa State University, Ames.

TABLE 3.13
Reproductive Stages

Stage	Abbreviated Title	Description
R1	Beginning bloom	One open flower at any node on the main stem
R2	Full bloom	Open flower at one of the two uppermost nodes on the main stem with a fully developed leaf
R3	Beginning pod	Pod 5 mm (3/16 in.) long at one of the uppermost nodes on the main stem with a fully developed leaf
R4	Full pod	Pod 2 cm (3/4 in.) long at one of the four uppermost nodes on the main stem with a fully developed leaf.
R5	Beginning seed	Seed 3 mm (1/8 in.) long in pod at one of the four uppermost nodes on the main stem with a fully developed leaf.
R6	Full seed	Pod containing a green seed that fills the pod cavity at one of the four uppermost nodes on the main stem with a fully developed leaf
R7	Beginning maturity	One normal pod on the main stem that has reached its mature pod color
R8	Full maturity	95% of the pods have reached their mature pod color; 5 to 10 days of drying weather are required after R8, before the soybeans have less than 15% moisture

Source: *Stages of Soybean Development*, Iowa State University, Ames.

TABLE 3.14
Comparison of Determinate and Indeterminate Soybeans

Determinate	Indeterminate
Little growth in height after flowering	Will usually double in height during flowering
Flowers occur about the same time throughout the plant	Will flower at new nodes; flowering, pod, and seed development occur at same time
Pods and seeds develop uniformly throughout the plant	Pods and seeds develop from lower nodes upward
Terminal leaves are approximately the same size as lower leaves	Terminal leaves are smaller than lower leaves
Terminal nodes on main stem usually have long, flowering stalks and several pods	Few pods at terminal node

3.2.3 Soybean Products, Standards, and Grades[1]

3.2.3.1 Soybean Processing Products

The National Soybean Processors Association defined product standards as follows:

Soybean cake or chip The product remaining after extraction of part of the oil by pressure or solvents. A term descriptive of the process of manufacture, such as expelled, hydraulic, or solvent-extracted shall be used in the brand name. The product is designated and sold according to its protein content.

Soybean meal Ground soybean cake, ground soybean chips, or ground soybean flakes. A term descriptive of the process of manufacture, such as expelled, hydraulic, or solvent-extracted, shall be used in the brand name. The product is designated and sold according to its protein content.

Soybean mill feed The by-product resulting from the manufacture of soybean flour or grits; composed of soybean hulls and the offal from the tail of the mill. A typical analysis is 13% crude protein, 32% crude fiber, and 13% moisture.

Soybean mill run The product resulting from the manufacture of dehulled soybean meal; composed of soybean hulls and bean meals that adhere to the hull in normal milling operations. A typical analysis is 11% crude protein, 35% crude fiber, and 13% moisture.

Soybean hull The product consisting primarily of the outer covering of the bean.

Solvent-extracted soybean flake The product obtained after extracting part of the oil by using hexane or homologous hydrocarbon solvents. The product is designated and sold according to its protein content.

Soybean flake and 44% protein soybean meal These are produced by cracking and heating soybeans and reducing the oil content of the conditioned product by using hexane or homologous hydrocarbon solvents. The extracted flakes are cooked and marketed as flakes or ground into meal. Typical analysis is minimum protein, 44%; minimum fat, 0.5%; maximum fiber, 7%; and maximum moisture, 12%.

Ground soybean Product obtained by grinding whole soybeans without cooking or removing any oil.

Ground soybean hay Ground plant that includes leaves and beans. It must be reasonably free of other crop plants and weeds and contain not more than 33% crude fiber.

Soybean feed, solvent-extracted The product remaining after partial removal of protein and nitrogen-free extract from dehulled solvent-extracted soybean flakes.

Heat processed (dry roasted) soybeans The product resulting from heating whole soybeans without removing any of the component parts. The product may be ground, pelleted, flaked, or powdered and must be sold according to its crude protein content.

Soy protein concentrate Concentrate prepared from high quality sound, clean, dehulled soybean seeds by removing most of the oil and water-soluble nonprotein constituents; must contain not less than 70% protein on a moisture-free basis.

Kibbled soybean meal The product obtained by cooking ground, solvent-extracted soybean meal under pressure and extruding from an expeller or other mechanical pressure device. It must be designated and sold according to its protein content and contain not more than 7% crude fiber.

Ground extruded whole soybean Meal product resulting from extrusion by friction, heat, and/or steam of whole soybeans without removing any of the components. It must be sold according to its crude protein, fat, and fiber content.

Soy grits Granu!ar material remaining from the screened and graded product after removal of most of the oil from selected, sound, clean, and dehulled soybeans by a mechanical or solvent extraction process.

Soy flour Finely powdered material resulting from the screened and graded product after removal of most of the oil from selected, sound, cleaned, and dehulled soybeans by a mechanical or solvent extraction process.

3.2.3.2 U.S. Standards and Grades

3.2.3.2.1 Definition of Soybean

Grain that consists of 50% or more of whole or broken soybeans (*Glycine max* (L.) Merr.) that will not pass through an 8/64 round-hole sieve and not more than 10% of other grains for which standards have been established under the U.S. Grain Standards Act.

3.2.3.2.2 Other Terms

Classes The two classes of soybeans are yellow and mixed.

Yellow soybeans Soybeans that have yellow or green seed coats. In cross-section, they are yellow or have a yellow tinge, and may include not more than 10% soybeans of other colors.

Mixed soybeans Soybeans that do not meet the requirements of the yellow soybean class.

Damaged kernels Soybeans and pieces of soybeans that are badly ground damaged, badly weather damaged, diseased, frost damaged, germ damaged, heat damaged, insect bored, mold damaged, sprout damaged, stinkbug stung, or otherwise materially damaged. Stinkbug stung kernels are considered damaged at the rate of 1/4 of the actual percentage of the stung kernels.

Foreign material All matter that passes through an 8/64 round-hole sieve and all matter other than soybeans remaining in the sample after sieving according to procedures prescribed in Federal Grain Inspection Service instructions.

Heat damaged kernels Soybeans and pieces of soybeans that are materially discolored and damaged by heat.

Purple mottled or stained kernels Soybeans that are discolored by the growth of fungus or by dirt or dirt-like substances, including nontoxic inoculants or other nontoxic substances.

Sieve (8/64 round-hole) Metal sieve 0.032 in. thick; perforated with 0.125 in. diameter round holes.

Soybeans of other colors Soybeans that have green, black, brown, or bicolored seed coats. Soybeans with green seed coats will also be green in cross-section. Bicolored soybeans will have seed coats of two colors, one of which is brown or black and covers 50% of the seed coats. The hilum of a soybean is not considered a part of the seed coat for this determination.

Split Undamaged soybean with more than 1/4 of the bean removed.

3.2.4 Production Statistics

TABLE 3.15
U.S. Soybean Acreage, Yield, and Production, 1991–2000

Year	Harvested Area (1,000 acres)	Yield (bu/acre)	Production (1,000 bu)
1991	56,011	34.2	1,986,539
1992	58,233	37.6	2,190,354
1993	57,307	32.6	1,669,718
1994	60,809	41.4	2,514,669
1995	61,544	35.3	2,174,254
1996	63,349	37.6	2,380,274
1997	69,110	38.9	2,686,750
1998	70,441	38.9	2,741,014
1999	72,446	36.6	2,653,758
2000	72,718	36.1	2,769,665

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 3.16
World Soybean Production, 1950–2000

Year	Total (million tons)	Per Person (kg)	Year	Total (million tons)	Per Person (kg)
1950	17	6.5	1984	93	19.5
1955	19	7.0	1985	97	20.0
1960	25	8.2	1986	98	19.8
1965	32	9.5	1987	103	20.6
1970	44	11.9	1988	96	18.7
1971	47	12.5	1989	107	20.6
1972	49	12.7	1990	104	19.7
1973	62	15.9	1991	107	20.0
1974	55	13.6	1992	117	21.5
1975	66	16.1	1993	118	21.3
1976	59	14.3	1994	138	24.5
1977	72	17.1	1995	125	22.0
1978	78	18.0	1996	132	22.9
1980	81	18.1	1997	158	27.0
1981	86	19.0	1998	160	27.0
1982	94	20.3	1999	158	26.3
1983	83	17.7	2000	167	27.5

Note: Preliminary.

Source: U.S. Department of Agriculture electronic database, December 2000.

TABLE 3.17
Leading Soybean-Growing States: Acreage, Yield, and Production, 2000

State	Acres Harvested (1,000)	Yield (bu/acre)	Production (1,000 bu)
Iowa	10,680	43.0	459,240
Illinois	10,450	44.0	459,800
Minnesota	7,150	41.0	293,150
Indiana	5,630	46.0	258,980
Missouri	5,000	35.0	175,000
Nebraska	4,575	38.0	173,850
Ohio	4,440	42.0	186,480
South Dakota	4,370	35.0	152,950
Arkansas	3,200	26.0	83,200
U.S. Total	72,718	38.1	2,769,665

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 3.18
Soybeans: Area, Yield, and Production by Continent and Country, 1999–2000

Location	Area (1,000 ha)	Yield (metric tons/ha)	Production (1,000 metric tons)
Continent			
North America	30,399	2.47	75,124
South America	23,769	2.42	57,413
Central America	27	2.63	71
European Union	365	3.12	1,140
Eastern Europe	270	2.47	666
Soviet Union	481	0.79	379
Middle East	113	1.65	186
Africa	830	0.71	586
Asia	15,883	1.39	21,999
Oceania	50	2.20	110
Country			
China	8,180	1.78	14,290
India	5,645	0.92	5,200
Indonesia	1,140	1.19	1,360
Nigeria	550	0.29	160
Russia	439	0.76	334
North Korea	300	1.00	300
Italy	239	3.41	814
Thailand	220	1.50	330
World Total	72,189	2.18	157,682

Source: Foreign Agriculture Service, Washington, D.C.

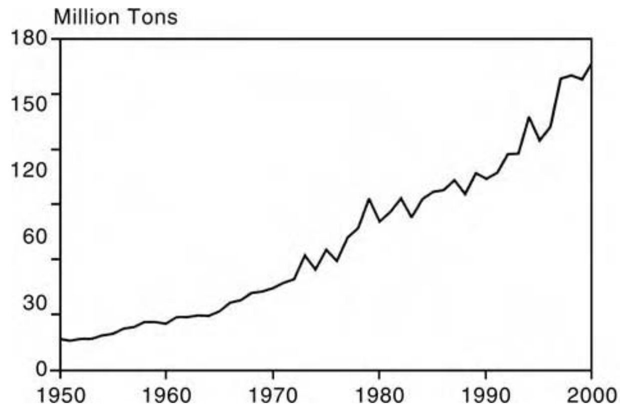


FIGURE 3.2 World soybean production, 1930–2000. (*Source*: *Vital Signs 2001*, Worldwatch Institute, W.W. Norton, New York.)

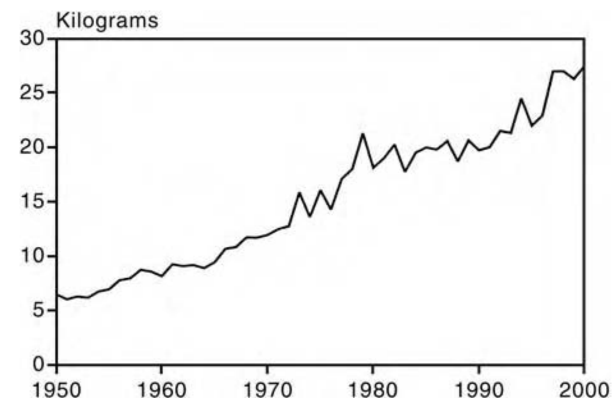


FIGURE 3.3 World soybean production per person, 1950–2000. (*Source*: *Vital Signs 2001*, Worldwatch Institute, W.W. Norton, New York.)

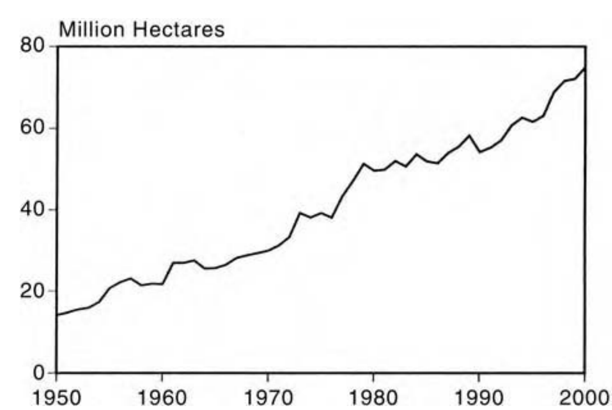
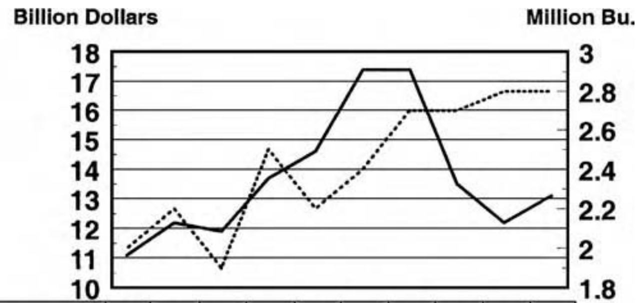


FIGURE 3.3 World soybean area harvested, 1950–2000. (*Source*: *Vital Signs 2001*, Worldwatch Institute, W.W. Norton, New York.)



Year	91	92	93	94	95	96	97	98	99	00
Production ----	2.0	2.2	1.9	2.5	2.2	2.4	2.7	2.7	2.8	2.8
Value of Prod.—	11.1	12.2	11.9	13.7	14.6	17.4	17.4	13.5	12.2	13.1

FIGURE 3.4 Production of soybeans and value of production, 1991–2000.

3.2.5 Fertilizer and Nutrient Element Uptake

TABLE 3.19
Percentages of Areas Receiving Fertilizer Applications, All States Surveyed, 1995–1999[a]

Year	Nitrogen	Phosphate	Potash
1995	17	22	25
1996	15	25	27
1997	20	26	33
1998	17	24	27
1999	18	26	28

[a] Acres receiving one or more applications of a specific fertilizer ingredient.

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 3.20
Uptake of Major Nutrient Elements for a 4-Ton/Acre Soybean Crop

Major Element	Weight (kg)
Nitrogen	350
Phosphorus as phosphate	65
Potassium as potash	180
Calcium	29
Magnesium	27
Sulfur	22

Source: International Soil Fertility Manual, 1995, Potash & Phosphate Institute, Norcross, GA. With permission.

TABLE 3.21
Nutrient Element Utilization (lb/acre) by 40- and 60-Bu/Acre Soybean Crops

Nutrient Element	Nitrogen	Phosphorus	Potassium	Magnesium	Sulfur
40 bu/A	224	53	97	18	17
60 bu/A	324	64	142	27	25

3.2.6 Nutrient Element Sufficiency

TABLE 3.22
Soybean Nutrient Element Sufficiency Ranges[a]

Major Elements	Sufficiency Range %
Nitrogen	4.00–5.50
Phosphorus	0.25–0.50
Potassium	1.70–2.50
Calcium	0.35–2.00
Magnesium	0.25–1.00
Sulfur	0.20–0.40
Micronutrients	**ppm**
Boron	20–55
Copper	10–30
Iron	50–350
Manganese	20–100
Molybdenum	1.0–5.0
Zinc	20–50

[a] Sampling procedure: 25 mature leaves from new growth prior to pod set.

Source: Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide, 1996, Micro-Macro Publishing, Athens, GA. With permission.

3.2.7 Composition of Seed

TABLE 3.23
Nutritive Values of Whole Soybean Seed

Component	Value
Calories/100 g	403
Protein, %	34.1
Fat, %	17.7
Total calcium, mg/lb	226
Total phosphorus, mg/lb	554
Total potassium, mg/lb	1,677
Carbohydrates, %	33.5

TABLE 3.24
Composition of Soybean Seed

Substance	%
Protein	34.1
Carbohydrate	33.5
Fat	17.7
Water	10.0
Ash	4.7

3.2.8 Nutrient Element Deficiencies[2]

3.2.8.1 Boron (B)

3.2.8.1.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Boron-deficient crops show poor growth, lack vigor, and yield poorly. Affected plants are very stunted and have stout stems and dark green leaves. If the deficiency persists and becomes severe, plants may die before setting pods. Mild deficiencies reduce branching and plant size and interfere with pollination and seed set, resulting in reduced grain yields. Severely deficient plants may either fail to branch or develop only a few flowers and pods, thereby producing little or no grain.

Interveinal chlorosis and necrosis of young leaves: Because B is not transferred from old to young leaves, symptoms develop first and are more severe on young leaves and are most severe on leaves that are still growing. Young leaves turn pale green and develop pale yellow interveinal chlorosis. Dark brown necrotic lesions appear in the chlorotic tissues. Old leaves remain dark green and appear healthy.

Deformed younger leaves: On severely affected plants, leaflets on the young leaves become deformed. The tips and sometimes the margins of the leaflets curl down and under.

Shortened internodes and deaths of buds: Boron deficiency greatly affects the growth of internodes and the development of apical and axillary buds. The upper internodes of the stems of affected plants are shortened, giving mildly deficient plants a rosette appearance. On severely deficient plants, the apical and axillary buds die and the young, undeveloped leaves or flowers turn pale brown.

3.2.8.1.2 Problem Soils

Boron deficiency is likely to occur in:

- Soils derived from parent material low in B, such as acid igneous rocks or fresh water sediments
- Sandy soils from which B has been leached by heavy rainfall
- Alkaline soils, especially those containing free lime
- Soils low in organic matter
- Acid peat and muck soils

3.2.8.1.3 Correcting Deficiency

Deficiencies can be corrected by applying soil dressings or foliar sprays of B fertilizers. Soil dressings are more effective if broadcast and mixed into the soil some months before sowing. Borax, boric acid, and chelated B compounds are suitable for soil application. Boric acid and chelated B compounds are suitable for foliar sprays and should be applied 5 to 6 weeks after

seedling emergence or as soon as symptoms appear. While soil dressings often remain effective for many years, foliar sprays must be reapplied to every crop.

Tests can estimate the amount of available B in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

3.2.8.2 Calcium (Ca)

3.2.8.2.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Calcium deficiency causes poor crop growth and can kill plants when severe. Affected plants are stunted and have short internodes, stout stems, and dark green, often distorted, leaves. If the deficiency occurs in old plants, the young leaves may develop yellow discolorations. Branching is reduced or even prevented if the deficiency is severe. Pod set may be severely reduced even by mild deficiencies. As a result, grain yields can be much lower than usual.

Deaths of young buds: Because Ca is not transferred from old to young tissues, symptoms are more severe on the youngest leaves that are still developing from buds. When a deficiency is severe, the youngest leaves and bud meristems die and turn brown.

Distorted young leaves: In young plants, the first leaves are distorted. Their tips fail to expand and become chlorotic, then develop pale brown necrosis. Tissue between the veins continues to expand, causing the margins to be cupped upward or downward. The bud meristems usually die quickly if the deficiency persists.

Chlorosis and necrosis of veins: When severe deficiencies develop in old plants, the bud meristems die and turn brown. The larger veins on young leaflets then become necrotic and turn brown. Yellow chlorosis develops in tissue adjacent to necrotic veins.

3.2.8.2.2 Problem Soils

Calcium deficiency is likely to occur in:

- Acid sandy soils from which Ca has been leached by heavy rainfall
- Strongly acid peat and muck soils that have low total Ca
- Alkaline or sodic soils in which exchangeable Na and pH are high and depress plant uptake of Ca
- Soil with high levels of soluble Al and low levels of exchangeable Ca

3.2.8.2.3 Correcting Deficiency

Calcium deficiency can be corrected by broadcasting a suitable fertilizer and mixing it into the soil some months before sowing. Where the problem is strictly a lack of Ca, suitable fertilizers are gypsum (calcium sulfate) and calcium nitrate or chloride. However, if the soil pH is low, lime, limestone (calcium carbonate), and dolomite (a mixture of calcium and magnesium carbonates) are more suitable.

A soil test can determine the lime or Ca requirements of a soil. However, since the correct rate of application depends on soil type and the crop to be grown, advice should be sought on fertilizer practices used on similar soils in the district. The excessive use of lime may induce deficiencies of K, Mg, Fe, Mn, Zn, and Cu so care should be taken to prevent overliming.

3.2.8.3 Iron (Fe)

3.2.8.3.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Soybeans seem to be relatively sensitive to Fe deficiency and affected crops are unthrifty and lack vigor. The plants are stunted and have thin, spindly stems, yellow young leaves, and dark green old leaves. Mild Fe deficiencies may not seriously reduce branching,

pod set, or grain yields, but severely deficient plants do not branch profusely and set fewer pods, greatly reducing grain yields.

Interveinal chlorosis on younger leaves: Because Fe is not readily transferred from old to young leaves, symptoms develop first and are more severe on leaflets of young leaves. The youngest, still expanding leaves are often the most severely affected if a deficiency persists. In mild deficiencies, pale yellow chlorosis develops in the interveinal areas of young leaflets. The veins remain green and easily seen. As the deficiency worsens, the veins fade and the chlorosis expands over entire leaflets. Old leaves remain dark green and appear healthy.

Necrotic lesions on veins of younger leaves: On severely affected plants, dark brown lesions develop on the veins of young leaflets. The lesions are more prominent on the undersurface of the leaflet and usually appear after the veins have turned yellow. The interveinal areas of affected leaflets may be puckered and the tips and margins of the leaflets curl down under the lamina.

Necrotic lesions on petioles and laminae of younger leaves: As symptoms develop, pale brown necrotic lesions appear on the petioles and margins of leaflets of younger leaves. These symptoms develop only after the whole leaves turn yellow and they can be used to distinguish between Fe and S deficiencies.

3.2.8.3.2 Problem Soils

Iron deficiency is likely to occur in:

- Alkaline soils in which levels of soluble Fe are low
- Waterlogged soils
- Acid soils with excessively high levels of soluble Mn, Zn, Cu, and Ni that depress Fe uptake
- Sandy soils low in total Fe
- Peat and muck soils whose organic matter ties up Fe

3.2.8.2.3 Correcting Deficiency

While dressings of inorganic Fe salts such as sulfates or chlorides have corrected deficiencies in some soils, the applied Fe quickly becomes insoluble and less available to plants. Iron salts of organic chelates are more promising as soil dressings because the chelate has the property of keeping Fe in solution. For acid soils, FeEDTA is the most effective chelate. FeHEDTA and FeDTPA are best on neutral soils and FeEDDHA is best for alkaline soils. However, large amounts of chelates may be required and this may prove too costly.

An equally effective remedy is to apply solutions of inorganic salts or chelates to the foliage (1% solutions or 1 kg salt per 100 L water per ha). Because Fe is so immobile in plants, sprays may need to be applied every 10 to 15 days to provide Fe to new leaves. Advice on fertilizer practices used on similar soils in the district should be sought to obtain the best remedy for the affected crop under local conditions.

3.2.8.4 Magnesium (Mg)

3.2.8.4.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Magnesium-deficient crops lack vigor and are pale green. Affected plants are slightly shorter than usual with thin, spindly stems and pale green to yellow leaves. Although branching is not reduced initially, deficient plants set fewer pods. The pods contain fewer seeds than usual and thereby reduce grain yields.

Interveinal chlorosis of older leaves: Symptoms begin as pale yellow, interveinal mottling on leaflets of middle leaves and spread rapidly to older leaflets. If the deficiency persists, these symptoms advance up the stems to younger leaflets.

Interveinal necrosis of older leaves: When a deficiency is severe, pale brown necrotic lesions appear in interveinal tissues in the bodies of the leaflets, advancing toward, but usually not reaching, the margins. The veins remain green and tissue near the veins may appear puckered.

3.2.8.4.2 Problem Soils

Magnesium deficiency is likely to occur in:

- Acid sandy soils from which Mg has been leached
- Strongly acid peat and muck soils that have low total Mg
- Soils that have been over-fertilized with Ca (for example, lime) or K, thus inhibiting Mg uptake

3.2.8.4.3 Correcting Deficiency

Magnesium deficiency on acid soils is corrected by broadcasting dolomite (a mixture of calcium and magnesium carbonates) and mixing it into the soil some months before sowing. When the problem is only a deficiency of Mg, band applications of magnesium sulfate or chloride can be made at or before planting.

Tests can estimate the amounts of soluble and exchangeable Mg in the soil, and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Magnesium deficiency in existing crops can be corrected by applying soluble salts, such as magnesium sulfate, chloride, or nitrate, with irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to meet crop requirements.

3.2.8.5 Manganese (Mn)

3.2.8.5.1 Deficiency Symptoms

Patchy, low-yielding crops: Soybeans are sensitive to Mn deficiency and affected crops often appear patchy. Plants in Mn-poor areas are stunted and have short, thin stems and pale green to yellow foliage. Affected plants produce less grain because branching is reduced and fewer pods are developed.

Mottled, interveinal chlorosis on younger leaves: Leaflets on the youngest leaves turn pale green and pale yellow mottling develops in interveinal areas. The veins remain green. Old leaves remain green and appear. This pattern of development occurs because manganese is not transferred from old to young leaves, and symptoms develop first and are more severe on younger leaves.

Brown necrotic lesions on younger leaves: As symptoms develop, small, brown lesions appear between the veins and the leaflets often curl downward.

Leaf fall of younger leaves: If a deficiency persists and becomes very severe, the affected young leaflets readily fall off, leaving bare stems and petioles on the upper parts of the plants. Mildly affected and healthy green leaves remain on the lower parts.

3.2.8.5.2 Problem Soils

Manganese deficiency is likely to occur in:

- Strongly alkaline soils in which Mn is less available to plants
- Poorly drained soils with high organic matter content in which Mn is tied up in forms less available to plants
- Strongly acid sandy soils from which soluble Mn has been leached by heavy rain
- Soils formed from rocks low in Mn

3.2.8.5.3 Correcting Deficiency

Foliar sprays and soil dressings of Mn salts and oxides have been used to correct deficiencies. Soil dressings are more effective when broadcast and mixed into the soil some weeks before sowing. However, foliar applications have generally been more successful. One or more foliar sprays of 0.5 to 1% solutions of soluble Mn salts (for example, 0.5 to 1 kg manganese sulfate per 100 L water per ha) usually correct the deficiency, the first to be applied 5 to 6 weeks after seedling emergence. If the symptoms reappear, sprays should be repeated immediately. While soil dressings usually last 5 to 6 years before fresh applications are needed, foliar sprays must be reapplied to every crop.

Tests can estimate the amount of available Mn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

3.2.8.6 Nitrogen (N)

3.2.8.6.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Rhizobium bacteria normally live in symbiosis with soybeans in the nodules attached to roots. The bacteria can fix atmospheric N_2 and supply all or most N requirements of the plant so N deficiencies are rare. However, they can occur if a crop is sown in N-deficient soil and the proper bacteria are not present naturally in the soil or not supplied at sowing, or if soil conditions prevent the bacteria from fixing N_2. Affected plants are stunted and have thin, spindly stems and small, pale green to yellow leaves. Deficient plants branch less profusely and set fewer pods that contain fewer seeds, resulting in low grain yields.

Pale yellow older leaves: Because N is readily transferred from old to young leaves, symptoms appear first and are more severe on old leaves, working up the plants to younger leaves if the deficiency persists. Young leaves remain pale green while old leaves fade from pale green through pale yellow to almost white. Eventually, the leaflets on affected leaves die, turn pale brown, and fall readily from the petioles.

Downward pointing leaflets: On healthy plants, the leaflets are carried in a horizontal plane, but on deficient plants, leaflets are often held with tips pointed toward the ground.

3.2.8.6.2 Problem Soils

Nitrogen deficiency is likely to occur in:

- Sandy soils that have been leached by heavy rainfall or excessive irrigation
- Soils low in organic matter
- Soils with a long history of cropping, whose N supplies have been exhausted

Even fertile soils may suffer temporary N deficiency when double-cropped, heavily leached, or waterlogged.

3.2.8.6.3 Correcting Deficiency

When soybeans are grown for the first time in a particular field, it is essential to treat the seeds before planting with a culture of the specified N_2-fixing bacteria. In some soils it may be advisable or even necessary to innoculate subsequent crops to ensure effective nodulation. If, for any reason, nodulation fails, N deficiency in existing crops can be corrected by applying soluble salts such as urea with irrigation water or as a foliar spray. Spray applications usually result in a rapid, short-lived response, and additional sprays 10 to 14 days apart may be necessary to meet crop N requirements.

3.2.8.7 Phosphorus (P)

3.2.8.7.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Soybeans demand high levels of P and young plants develop easily recognizable symptoms. Affected crops lack vigor. The plants are stunted and have thin, spindly stems and small, bluish-green leaves. Phosphorus deficiency delays maturity and reduces branching, the number of pods produced, and the number of seeds per pod. As a result, grain yields can be severely reduced.

Brown necrotic lesions on older leaves: Symptoms are clearly recognizable even when a deficiency is mild. All leaves are dull bluish-green, and the leaflets are smaller than usual. Small, dark brown necrotic lesions appear in interveinal areas on leaflets of old leaves. As the symptoms develop, the lesions become surrounded by dark yellow chlorosis. The symptoms appear first and are more severe on old leaves, working up the plants to young leaves if the deficiency continues.

Dark yellow older leaves: In severe deficiencies, leaflets of old leaves turn dark yellow and the interveinal tissue is covered by small, dark brown necrotic lesions. As the leaflets die, they turn dark orange then brown and fall readily, leaving the petioles attached to the stems. Eventually, the petioles are shed.

Downward pointing leaflets: Older leaflets on healthy plants are carried in a horizontal plane. On deficient plants the tips of affected leaflets point toward the ground.

3.2.8.7.2 Problem Soils

Phosphorus deficiency is likely to occur in:

- Soils low in organic matter
- Soils with a long history of cropping and exhausted P supplies
- Highly weathered, Fe-rich soils whose phosphate is fixed in less available forms
- Soils whose topsoil has been lost through erosion
- Alkaline soils whose P may be tied up in insolube phosphates that are less available to plants

3.2.8.7.3 Correcting Deficiency

Phosphorus deficiency can be corrected by applying phosphatic fertilizers to the soil at or before sowing. Suitable fertilizers are single or triple superphosphates and ammonium phosphates. Growth depends on the amounts of water-soluble phosphates and the rates of exchange between soluble and insoluble forms of P in the soil.

Tests can estimate the amount of available phosphate in a soil and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Phosphorus deficiency in existing crops can be corrected by applying soluble salts such as ammonium phosphates with irrigation water. Spray applications of similar salts are usually not recommended because of the large number needed to supply crop requirements.

3.2.8.8 Potassium (K)

3.2.8.8.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Like other legumes, soybeans have a great need for K. Deficient crops lack vigor and mature more slowly than usual. Affected plants are short and have thin stems and pale green older leaves. Potassium deficiency delays branching and reduces the number of pods set and the number of seeds per pod. Severely deficient plants may produce deformed seeds.

Marginal necrosis on older leaves: Symptoms appear first and are more severe on old leaves because K is readily transferred from old to young leaves when a deficiency occurs. While the

youngest leaves remain dark green and appear healthy, old leaves develop pale brown marginal necrosis. The necrotic lesions appear in interveinal tissues on or near the margins, usually toward the tips of the leaflets. As more K is withdrawn, the lesions join and advance along the margins toward the bases of the leaflets. If the deficiency persists, the symptoms move up the plants to younger leaves.

Dark yellow older leaves: When a deficiency is very severe, leaflets on old leaves develop general, dark yellow chlorosis before dying, turning dark brown, and falling from the plants.

Red veins on older leaves: When a sudden, severe deficiency occurs, leaflets on middle and older leaves may become distorted and develop red lesions on the main veins before other symptoms appear. Reddening of the veins is more noticeable on the undersides. The interveinal tissue becomes puckered and the tips of the leaflets curl downward.

Necrotic lesions on petioles of older leaves: On severely deficient plants, dark brown necrotic lesions develop on the petioles, which then collapse. The leaves hang down around the stems before the leaflets die and fall from the plants.

3.2.8.8.2 Problem Soils

Potassium deficiency is likely to occur in:

- Soils low in organic matter after many years of cropping
- Sandy soils formed from parent material low in K
- Light-textured soils from which K has been leached by heavy rainfall

3.2.8.8.3 Correcting Deficiency

Potassium deficiency is corrected by applying potassium nitrate, sulfate, or chloride to the soil at or before sowing. Crop yield depends on the amounts of water-soluble and exchangeable K in the soil. Tests can measure the amount of available K and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the region.

Potassium deficiency in existing crops can be corrected by applying soluble K salts, such as potassium sulfate, chloride, or nitrate, with irrigation water. The foliar application of similar salts is usually not recommended because of the large number needed to supply crop requirements.

3.2.8.9 Sulfur (S)

3.2.8.9.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Sulfur deficiency causes unthriftiness, lack of vigor and delayed maturity. Whole plants in young crops may be pale green, but in more mature crops, plants are stunted and have thin stems. Only young leaves are pale green to yellow. Affected plants produce fewer branches that set fewer pods containing fewer seeds than usual. As a result, grain yields are reduced.

Pale yellow younger leaves: Because S is not readily transferred from old to young leaves, symptoms appear first and are more severe on young leaves. Old leaves remain green and appear healthy. In young crops, whole plants may appear pale green and the youngest leaves will be yellowest. As the crop matures, leaflets on young leaves turn pale yellow while those on old leaves remain green.

3.2.8.9.2 Problem Soils

Sulfur deficiency is likely to occur in:

- Soils low in organic matter after many years of cropping
- Soils formed from parent material low in S (for example, some volcanic rocks and ash)
- Acid, sandy soils from which sulfates have been leached

3.2.8.9.3 Correcting Deficiency

Soil dressings of any S fertilizer will correct deficiencies. Elemental S (flowers of sulfur) may be broadcast and thoroughly mixed into soil about 4 months before sowing in alkaline soils. Gypsum (calcium sulfate) is a useful source of S in neutral and acidic soils.

Tests can measure the amount of available sulfate in the soil before sowing and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Sulfur deficiency in existing crops can be corrected by applying soluble salts, such as magnesium, ammonium, or potassium sulfate, in irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to supply crop requirements.

3.2.8.10 Zinc (Zn)

3.2.8.10.1 Deficiency Symptoms

Patchy, low-yielding crops: Soybeans are relatively sensitive to Zn deficiency. Affected crops grow poorly, lack vigor, and mature slowly. The plants are very stunted and have thin, short stems and pale green, bronzed foliage. Zinc-deficient plants develop fewer pods than normal, resulting in reduced grain yields.

Yellow mottling on older leaves: The earliest symptom is pale yellow mottling in interveinal areas on leaflets of middle leaves. The yellow mottling then appears in older leaves until they are all pale yellow; young leaves remain green and appear healthy. If the deficiency persists, these symptoms move up the plants to younger leaves.

Bronze necrosis on older leaves: When a deficiency is very severe, small, bronze necrotic lesions develop in the chlorotic interveinal areas of old leaflets. The veins remain green but the leaf edges cup downward and the leaflets point toward the ground. Eventually, the leaflets die, turn pale brown, and fall readily from the petioles.

3.2.8.10.2 Problem Soils

Zinc deficiency is likely to occur in:

- Strongly alkaline soils where the availability of Zn is depressed
- Leached sandy soils whose total Zn is low
- Leveled soils whose Zn-deficient subsoils may be exposed on the surface
- Soils in which heavy applications of phosphatic fertilizers may have reduced the use of Zn by crops

3.2.8.10.3 Correcting Deficiency

Foliar and soil applications of Zn salts have been used to correct deficiencies. Soil dressings of zinc chelates, sulfates, or oxides should be broadcast and mixed into the soil 2 to 3 months before sowing. Soil-applied Zn has a residual effect for 6 to 8 years before fresh applications are needed. Foliar sprays have no residual effects and fresh applications must be made to each crop. Best results are obtained when a 0.5 to 1% solution of a soluble Zn salt (for example, 0.5 to 1 kg zinc sulfate heptahydrate per 100 L water per ha) is applied 2 to 3 weeks after seedling emergence. Additional sprays should be applied as soon as symptoms reappear.

Tests can estimate the amount of available Zn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

3.2.9 Manganese and Sodium Chloride Toxicity[2]

3.2.9.1 Manganese (Mn) Toxicity

3.2.9.1.1 Symptoms of Toxicity

Unthrifty, low-yielding crops: Soybeans appear to be more tolerant of high levels of Mn than many other crops. Affected crops lack vigor and show poor growth. Plants are stunted and have short, stout stems and dark green leaves. If the toxicity persists and becomes severe, branching is reduced and plants set fewer pods that contain fewer seeds than usual.

Necrotic lesions on older leaves: Excess Mn is carried in transpiration streams and accumulates in older tissues. Symptoms develop first and are more severe on old leaves, working up the stems to young leaves if the toxicity persists. Leaflets on old leaves remain dark green and develop pinpoint, red-brown necrotic lesions on their upper surfaces. The lesions tend to concentrate in tissues adjacent to the larger veins.

Red-brown lesions: All veins develop red-brown lesions on veins of older leaves when a deficiency is severe. Although the lesions are more prominent on the undersides, they are easily seen on the upper surfaces.

Yellow mottling on youngest leaves: The leaflets on the youngest leaves are smaller than usual and develop pale yellow, interveinal mottling. As the leaflets mature, the mottling disappears and is replaced by red-brown necrotic lesions.

3.2.9.1.2 Problem Soils

Manganese toxicity is likely to occur in:

- Strongly acid soils that show increased solubility of Mn
- Waterlogged soils in which poor aeration reduces unavailable manganic (Mn^{3+}) ions to manganous (Mn^{2+}) ions that can be taken up by plants

3.2.9.1.3 Correcting Toxicity

Manganese toxicity is usually corrected by management practices that reduce levels of soluble Mn in soil. If soils are strongly acid, liming to an alkaline reaction will reduce excess levels of soluble Mn. Drainage of waterlogged soils prevents anaerobic conditions that produce soluble Mn^{2+} ions. If soils are over-treated with Mn^{2+} fertilizers, heavy leaching with low-Mn irrigation waters or mulching with organic materials removes soluble Mn.

3.2.9.2 Sodium Chloride (NaCl) Toxicity

3.2.9.2.1 Symptoms of Toxicity

Unthrifty, low-yielding crops: Soybeans are more sensitive to excess NaCl than many other summer crops. Affected crops show poor growth, lack vigor, and appear harsh and droughty. Plants may appear wilted and have short, thin stems and small, pale green and grey foliage. The number of pods set and the number of seeds per pod are both reduced and grain yields are low.

Droughty, limp appearance: When high soil concentrations of NaCl occur, plants have difficulty obtaining sufficient water for normal growth. Affected plants often have harsh, droughty appearance and wilt readily on hot days even when ample water is available. Wilted plants may recover overnight but eventually permanently wilted.

Grey necrosis on older leaves: Because NaCl is carried in transpiration streams, it accumulates in older tissues. Therefore, symptoms appear first and are more severe on old leaves and work up the plants to young leaves if the toxicity persists. Leaflets on older leaves wilt and grey necrosis develops on the margins near the tips. The necrosis advances rapidly into interveinal areas until only the veins remain green. If the toxicity persists, the leaflets or entire plants die and turn pale brown.

3.2.9.2.2 Problem Soils

Sodium chloride toxicity is more likely to occur in:

- Saline soils formed from salt water sediments
- Previously fertile soils that have been flooded or heavily irrigated with water containing high concentrations of NaCl

3.2.9.2.3 Correcting Toxicity

Leaching with good quality irrigation water is the most effective means of removing excess Na and Cl from soil. The water table may have to be lowered. Permeable soils such as well structured sandy soils are often easily reclaimed, but the problem is more difficult in less permeable soils (for example, poorly structured heavy clays).

If exchangeable Na in the soil is high, reclamation involves replacement of the adsorbed Na with Ca by applying gypsum (calcium sulfate) and then leaching the dissolved Na and Cl beyond the rooting depths of the plants. If irrigation water is to be used to leach the Na, its quality should be checked before use to ensure it is not saline. Where excess NaCl cannot be wholly corrected by soil leaching, a more tolerant species may have to be grown.

3.2.10 Weights and Measures

One bushel of soybean grain has an approximate net weight of 20 lb or 27.2 kg. One gallon of soybean oil has an approximate net weight of 7.7 lb or 3.5 kg.

TABLE 3.25
Weight and Standard Yield of Level Full Bushel of Soybean Grain

Weight of 1 measured bu (lb)	Multiplication factor to yield standard bu
64	1.07
62	1.03
60	1.00
58	0.97
56	0.93
54	0.90
52	0.87
50	0.83
48	0.80
46	0.77
44	0.73
42	0.70
40	0.67

TABLE 3.26
Soybean Seeds/lb, Weight/bu, and Germination Time

Seeds/lb (1,000)	Seeds/g (no.)	Weight/bu (lb)	Germination time (days)
2–3	6–13	60	8

REFERENCES

1. Smith, C.W., *Crop Production: Evolution, History, and Technology*, 1995, John Wiley & Sons, New York.
2. Grundon, N.J., *Hungry Crops: A Guide to Nutrient Deficiencies in Field Crops*, 1987, Queensland Department of Primary Industries, Brisbane, Australia.

4 Cotton (*Gossypium* spp.) Fiber

4.1 INTRODUCTION

Cotton belongs to the Malvaceae family. It is known as coton in French, cottone in Italian, algodon in Spanish, baumwolle in German, and algodao in Portuguese. Cotton is unique among cultivated crops in that four distinct species were domesticated — two in the Old World and two in the New World. Various theories were proposed regarding the origins and development of the New World tetraploid cotton grown today from the Old World diploid species.

Of the identified 39 species of cotton, *upland* cotton, *Pima*, also called Egyptian and American-Egyptian cotton, tree cotton, and Levant cotton are the only ones grown today. All four have different characteristics such as plant height, type of fiber, blooming time, and flower color. Upland cotton is cultivated in many parts of the world. Fiber length varies from 3/4 to 1-1/4 in. Pima, Egyptian, and American-Egyptian fibers range in length from 1-1/4 to 1-1/2 in. and are stronger than those of upland cotton. Old World, tree, and Levant cotton are low-yielding types and their fibers are coarse and short.

Although most cotton is produced for fiber, cottonseed oil is an important commodity. The 37.1 million short tons produced in 1999 represent 11% of all vegetable oil produced.

Although cotton is considered a tropical species, it is grown mostly in temperate regions where summer temperatures are hot (25 to 35°C) and more than 200 days are frost-free. Sunny weather after the bolls open helps dry the fibers for harvest. Cotton grows best in fertile (pH 6.0 to 8.0), well drained soil that receives adequate moisture during the growing season. Cotton grown in the western U.S. is normally irrigated.

Periodic petiole analysis for nitrate (NO_3) content is used to regulate fertilization, particularly of N, to ensure balance between vegetative growth and boll set and development. In 1982, the highest verifiable cotton yield of 5.4 bales per acre was recorded in Arizona. In the U.S. in 2000, the average cotton yield was 635 lb or 1.3 bales per acre.

4.2 TERMS AND GLOSSARY[1]

4.2.1 TERMS

Bale Bundle of raw cotton; in the U.S., a bale weighs about 500 lb (227 kg).
Boll Rounded, mature seed pod of the cotton plant.
Boll weevil Beetle whose young feed on cotton squares (buds), causing the squares to fall off the plants.
Bur Opened seed case of the cotton plant.
Carding Process of cleaning and straightening cotton fibers.
Drawing Process that further straightens cotton fibers after carding and forms them into a loose rope called a *drawn sliver* (pronounced *SLY vuhr*).
Ginning Separating cotton fibers from seeds.
Gray-state cloth Cotton fabric in its natural grayish-white state before bleaching or dyeing; also called *gray goods* or *greige* (pronounced *gray*).
Lint Raw, ginned cotton that is ready for baling.
Linters Short fibers that remain on cotton seed after ginning.

Mercerization Application of an alkaline solution to cotton cloth or thread to strengthen the cotton, make it hold dye better, and give it luster.
Picker Machine that separates and cleans cotton fibers.
Pima cotton Cotton composed of strong, silky fibers that is used to make fine, smooth fabrics.
Roving Thin strand of cotton fiber ready for spinning.
Sizing Sliver Pronounced *SLY vuhr*; a loose rope of cotton fibers. A card sliver is thicker and has more tangled fibers than a drawn sliver.
Squares Buds of cotton blossoms.
Staple Average lengths of cotton fibers.
Trash Leaves, stems, and other unwanted plant materials in harvested cotton.
Upland cotton Most common type of cotton.

4.2.2 Glossary

Anther Upper portion of the stamen that contains pollen grains.
Bast fiber Coarse fiber made from plant conductive tissues (e.g., phloem fibers).
Boll Cotton fruit that consists (after fertilization) of the carpel wall, placental column, seeds, and cellulose fibers.
Bracts Modified leaves subtending the floral buds and later the bolls.
Calyx First series of floral organs, immediately external to the flower buds and later the bolls; consists of five sepals.
Carpel Organ-bearing ovules along the inside margins; a unit of structure of a compound pistil; upland cotton may have three to six (usually four); Pima has three.
Chalazal cap Large end of a seed or ovule where its parts merge.
Corolla Collectively, the five petals of a cotton flower.
Cotyledon Rudimentary or first leaves found inside a seed; the seed leaves of the embryo.
Filament Lower portion of the stamen that supports the anther.
Fruiting branch Branch on which pedicled fruits are borne directly from branches; terminates in a fruit; subtending leaf lateral extension is via axillary bud break; also called a *sympodium*.
Glabrous Having no hairs or pubescence.
Gossypol gland Gland found in all above-ground plant tissue; contains gossypol and related compounds that are toxic to nonruminant animals.
Hirsute Having pubescence or hairs on stems or leaves.
Hull Seed coat or outer covering removed by milling.
Lint Cellulose fibers resulting from elongation of seed epidermal cells.
Linters Fibers too short to be removed during ginning and fiber stumps left on seeds after normal ginning; linters are removed at oil mills and used in a variety of industrial products and as padding in seats and furniture.
Micropyle Pointed end of a seed; opening in the integument of the ovule.
Nectary Specialized structure or gland that exudes sugary nectar.
Ovary Swollen basal portion of the pistil, contains the ovules or seeds.
Ovule Female egg containing a haploid number of chromosomes.
Peduncle Stalk supporting a flower; also called a *pedicle*.
Petiole Stalk supporting a leaf.
Phyllotaxy Distribution or arrangement of leaves on a stem; expressed as a fraction
Pistil Female portion of a flower composed of the stigma, style, and ovary.
Raphe Broad seam or mid-vein of a seed.
Sepal One of the units of the calyx; a modified leaf.
Stamen Male portion of a flower composed of filaments and anthers.
Stigma Part of the pistil that receives pollen grain.
Style Portion of the pistil between the stigma and the ovary.

Vegetative branch Branch that does not directly bear fruit; reproductive branches that directly bear fruit may originate from vegetative branches.

4.3 PRODUCTION STATISTICS

TABLE 4.1
U.S. Cotton Acreage, Yield, and Production, 1991–2000

Year	Harvested Acres (1,000)	Yield (lb/acre)	Production (1,000 bales)[a]
1991	12,959.5	652	17,614.3
1992	11,123.3	700	16,216.5
1993	12,763.3	606	16,133.6
1994	13,322.3	706	19,662.0
1995	16,006.7	537	17,899.8
1996	12,686.1	705	18,942.0
1997	13,406.0	673	18,790.0
1998	10,683.6	625	13,918.2
1999	13,424.9	607	16,966.0
2000[b]	13,097.5	631	17,219.5

[a] 480-lb net weight bales.
[b] Preliminary.

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 4.2
Cotton Area, Yield, and Production of Continents and Specified Countries, 1999–2000

Location	Area (1,000 ha)	Yield (kg/ha)	Production (1,000 bales)[a]
Continent			
North America	5,565	688	17,637
South America	1,450	666	4,455
Central America	10	501	23
European Union	543	1,041	2,596
Eastern Europe	17	410	32
USSR	2,465	645	7,305
Middle East	1,250	1,042	5,983
Africa	4,611	325	6,883
Asia	15,755	539	39,028
Australia	464	1,595	3,400
Country			
India	8,646	311	12,337
U.S.	5,433	680	16,968
China	3,726	1,028	17,600
Pakistan	2,915	642	8,600
Uzbekistan	1,500	752	5,180
World Total	32,177	591	87,357

[a] Bale = 480 lb.

Source: Foreign Agriculture Service, Washington, D.C.

TABLE 4.3
Acreage, Yield, and Production of Leading Cotton-Producing States, 2000

State	Area Harvested (1,000 acres)	Yield (lb/acre)	Production (1,000 bales)[a]
		Upland Cotton	
Texas	4,400	431	3,950
Georgia	1,350	583	1,640
Mississippi	1,280	649	1,730
Arkansas	950	733	1,450
North Carolina	925	747	1,440
California	770	1,371	2,200
Louisiana	695	628	910
Alabama	530	489	540
U.S. Total	12,927	625	16,822
		Pima Cotton	
California	144	1,167	350
Texas	16	900	30
U.S. Total	170.5	1,119	397.5

[a] 480-lb net weight bales.

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

4.4 FERTILIZER TREATMENT

TABLE 4.4
Fertilizer Application Total Acreage and Areas Receiving Applications, All States Surveyed, 1995–1999[a]

Year	Nitrogen (%)	Phosphate (%)	Potash (%)
1996	77	55	43
1997	90	67	58
1998	84	66	53
1999	86	59	52

[a] Acres receiving one or more applications of a specific fertilizer ingredient.

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

4.5 NUTRIENT ELEMENT UPTAKE

TABLE 4.5
Uptake of Major Elements and Micronutrients for a 1.7-Ton/Acre Cotton Lint Crop

Major Elements	kg
Nitrogen	200
Phosphorus as phosphate	57
Potassium as potashg	95
Calcium	14
Magnesiumg	23
Sulfur	20
Micronutrients	**g**
Boron	120
Copper	110
Iron	140
Manganese	190
Molybdenum	2
Zinc	480

Source: International Soil Fertility Manual, 1995, Potash & Phosphate Institute, Norcross, GA. With permission.

TABLE 4.6
Nutrient Element Uptake and Removal by 2,500 kg/ha Cotton Crop

Major Elements	kg/ha
Nitrogen	156
Phosphorus	36
Potassium	151
Calcium	168
Magnesium	40
Micronutrients	**g/ha**
Boron	3
Copper	120
Iron	2,960
Manganese	250
Zinc	116

TABLE 4.7
Nutrient Element Utilization (lb/acre) by Cotton Crop

	Yield Level	
Nutrient Element	1,000 lbs/acre	2,000 lbs/acre
Nitrogen	149	180
Phosphorus as phosphate	51	63
Potassium as potash	112	126
Magnesium	32	35
Sulfur	28	30

4.6 NUTRIENT ELEMENT SUFFICIENCY (LEAF AND PETIOLE ANALYSIS)

TABLE 4.8
Nutrient Element Sufficiency Ranges

	Sufficiency Range[a]	
Major Elements	**First Squares to Initial Bloom**	**Full Bloom**
	%	
Nitrogen	3.50–4.50	3.00–4.30
Phosphorus	0.30–0.50	0.25–0.45
Potassium	1.50–3.00	0.90–2.00
Calcium	2.00–3.00	2.20–3.50
Magnesium	0.30–0.90	0.30–0.80
Sulfur	0.25–0.80	—
Micronutrients	**ppm**	
Boron	20–60	20–60
Copper	5–25	5–25
Iron,	50–250	40–300
Manganese	25–350	30–300
Zinc	20–200	20–100

[a] Sampling procedure: Column 2, 25 vegetative stems, first squares to initial bloom; Column 3, vegetative stems, full bloom.

Source: Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide, 1996, MicroMacro Publishing, Athens, GA. With permission.

TABLE 4.9
Petiole Nitrate-Nitrogen (NO_3-N) Levels for Sufficiency (ppm)

	Nitrate-Nitrogen Content			
Status	**First Square**	**First Flowers**	**First Bolls**	**First Open Bolls**
Sufficient	18,000	12,500	7,000	3,500
Deficient	12,000	7,500	3,000	1,500

Source: *IFA World Fertilizer Use Manual*, 2000, International Fertilizer Industry Association, Paris.

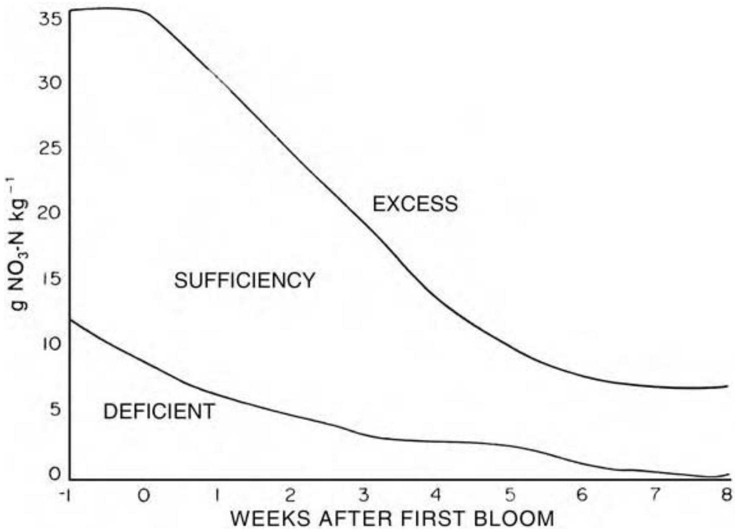


FIGURE 4.1 Sufficiency range for cotton petiole nitrate (NO_3) in Arkansas.

4.7 NUTRIENT ELEMENT DEFICIENCIES

TABLE 4.10
Nutrient Element Deficiency Symptoms

Symptom	Deficient Element
Causal parasites or viruses absent	All deficiencies
Localized effects and decreased growth	All deficiencies
Effects localized on older or lower leaves or generalized on whole plant	
Local symptoms occurring as mottling or chlorosis with or without necrotic spotting (areas of dead tissue) on lower leaves; little or no drying up of lower leaves	
Lower leaves brittle, curved, or cupped under; yellowish-white mottling between veins; necrotic spots	Potassium
Lower leaves purplish-red with green veins	Magnesium
Symptoms general; yellowing and drying or firing of lower leaves	
Plants light green; lower leaves yellow, drying to brownish color	Nitrogen
Plants dark green; leaves and plants small; maturity delayed Phosphorus	
Pronounced interveinal chlorosis and bronzing of leaves that become brittle with upturned margins; maturity delayed	Zinc
Effects localized on terminal growth (newer or bud leaves)	
Dieback involving terminal buds, resulting in many-branched plant	
Young leaves; yellowish-green flower buds; chlorosis; early indications are banded petioles and ruptured peduncles	Boron
Terminal buds remain alive; chlorosis of upper or bud leaves; leaves yellowish-gray or reddish-gray with green veins	Manganese
Young leaves first affected, turning pale green; older leaves remain greener; plants dwarfed	Sulfur

TABLE 4.11
Nutrient Element Deficiency Descriptions

Element	Deficiency Symptom
Nitrogen	Reduced yield and quality; visible symptoms are light green plants; lower leaves drying to brownish color
Phosphorus	Plants are short and small; growth is retarded; maturity is postponed; typical symptoms are loss of chlorophyll and development of discolored red leaves
Potassium	Plants are susceptible to stem blight leading to premature senescence; typical symptoms are bronzing and marginal necrosis of leaves adjacent to developing bolls; plants fully necrotic; premature defoliation
Magnesium	Lower purplish red leaves with green veins
Sulfur	Dwarfed plants with green leaves
Manganese	Leaves are yellowish or reddish grey with green veins
Zinc	Small leaves with interveinal chlorosis and shortened stems giving plants a small bushy appearance; slow in development; leaves lose green color and develop necrotic spots
Boron	Plants produce clittelums and dieback of terminal buds that do not blossom and decrease production; young leaves turn yellowish green; flower buds chlorotic

4.7.1 Boron (B)

4.7.1.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Mildly deficient crops lack vigor and yield poorly. Affected plants are stunted and have short, stout stems and dark green leaves. Branching may not be reduced but branches are shorter than usual and give the plant a bushy look. Flower production is lower and few bolls may set. In severely deficient crops, the plants often die before flowers are formed.

Dark green, vertical younger leaves: All leaves are dark green. Young leaves hang down and point toward the ground, with their margins cupped under so that they appear to fold around the upper stems. Old leaves remain flat and are held more horizontally.

Shortened internodes and deaths of apical buds: Because B is not transferred from old to young leaves, the youngest tissues are the most affected. The upper internodes are very short and the youngest leaves crowd together at the shoot tips. Young buds often die, preventing further growth of the stems. Many lateral branches appear but their apical buds also die. Entire plants die if the deficiency persists.

4.7.1.2 Problem Soils

Boron deficiency is likely to occur in:

- Soils derived from parent material low in B, such as acid igneous rocks or freshwater sediments
- Sandy soils from which B has been leached by heavy rainfall
- Alkaline soils, especially those containing free lime
- Soils low in organic matter
- Acid peat and muck soils

4.7.1.3 Correcting Deficiency

Boron deficiency can be corrected by soil dressings or foliar sprays of B fertilizers. Soil dressings are more effective if broadcast and mixed into the soil some months before sowing. Borax, boric acid, and chelated boron compounds are suitable for soil application. Boric acid and chelated B compounds

are suitable for foliar sprays that should be applied 5 to 6 weeks after seedling emergence or as soon as symptoms appear. While soil dressings often remain effective for many years before fresh applications are needed, foliar sprays have no residual value and must be reapplied to every crop.

Tests can estimate the amount of available B in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

4.7.2 Calcium (Ca)

4.7.2.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Mildly deficient crops are unthrifty, lack vigor, and yield poorly. Affected plants are stunted and have thin stems and dark green leaves. They appear wilted, with stems bent over and leaves and petioles hanging limply down around the stems. Branching is severely reduced and fewer flowers and bolls are produced. Yields of lint and seed are very low. In severe deficiencies, the apical buds die, causing many plants to die before maturity.

Wilted plants: Deficient plants wilt even when ample water is available. The stems bend over and the leaves and petioles hang limply down around the stems.

Shortened internodes and deaths of apical buds: Because Ca is not transferred from old to young tissues, symptoms are more severe in developing tissues. The internodes at the tops of the shoots fail to elongate and give the plants a bushy or rosetted appearance. The young buds at the top of the main shoots and the stems immediately below them turn dark brown and die. The lateral buds in the axils of the leaves begin to grow, then brown and die. Similar brown lesions appear on the bases of petioles, causing the leaves to die. All severely affected plants eventually die.

4.7.2.2 Problem Soils

Calcium deficiency is likely to occur in:

- Acid sandy soils from which Ca has been leached by heavy rainfall
- Strongly acid peat and muck soils whose total Ca is low
- Alkaline or sodic soils in which exchangeable Na and pH are high, thus depressing Ca uptake by plants
- Soil with high levels of soluble Al and low levels of exchangeable Ca

4.7.2.3 Correcting Deficiency

Calcium deficiency can be corrected by broadcasting a suitable fertilizer and mixing it into the soil some months before sowing. Where the problem is only a lack of Ca, suitable fertilizers are gypsum (calcium sulfate) and calcium nitrate or chloride. If the soil pH is low, lime or limestone (calcium carbonate) and dolomite (a mixture of calcium and magnesium carbonates) are more suitable.

Tests can determine lime or Ca requirements. The correct application rate application depends on soil type and the crop to be grown. Advice should be sought on fertilizers used on similar soils in the district. Excessive lime use may induce deficiencies of K, Mg, Fe, Mn, Zn, and Cu, and care should be taken to prevent overliming.

4.7.3 Copper (Cu)

4.7.3.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Copper deficiency is rare in cotton and the only signs of disorders may be unthriftiness and poor yields. Affected plants are stunted and have short stems and dull green leaves. Branching is reduced and severely deficient plants may not branch. Fewer flowers are produced and the number of bolls set is reduced.

Wilted plants: The leaves of Cu-deficient plants appear limp and wilted. The leaves are held almost vertically with the tips and margins cupped or pointed downward.

Interveinal chlorosis on older leaves: As symptoms progress, faint, dull yellow interveinal chlorosis develops on old leaves. The veins and adjacent tissues remain dark green. If the deficiency persists, the symptoms advance up the plants to young leaves. The youngest leaves remain dark green but may be smaller than usual.

4.7.3.2 Problem Soils

Copper deficiency is likely to occur in:

- Peat and muck soils whose organic matter ties up soluble Cu in forms less available to plants
- Alkaline sands whose total Cu is low
- Leached acid soils that have low total Cu
- Soils formed from rocks low in Cu

4.7.3.3 Correcting Deficiency

Foliar sprays and soil dressings of salts such as copper sulfate (bluestone) or copper chelates have corrected Cu deficiencies. Soil dressings should be applied and mixed into the soil some weeks before sowing. However, they may fail to correct deficiencies in some seasons and symptoms may reappear. If this occurs, foliar sprays should be applied immediately. A reliable remedy is to apply foliar sprays of 0.5 to 1% solutions of soluble Cu salts (for example, 0.5 to 1 kg copper sulfate per 100 L water per ha), the first applied 4 to 6 weeks after seedling emergence. Additional sprays should be applied as soon as symptoms reappear.

Tests can estimate the amount of available Cu in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

4.7.4 Iron (Fe)

4.7.4.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Iron-deficient crops lack vigor and yield poorly. Affected plants are only slightly smaller than usual unless a deficiency has been prolonged. They then become shorter and develop thin stems and pale green to yellow foliage. Branching, flower production, and boll set may not be greatly affected unless the deficiency persists, in which case all will be reduced.

Interveinal chlorosis on younger leaves: Because Fe is not transferred from old to young leaves, symptoms appear first and are more severe on young leaves. Old leaves remain dark green and appear healthy. Pale green to yellow interveinal chlorosis develops on young leaves. The veins remain green and prominent during the early stages of symptom development but fade to become barely visible when the deficiency persists. Affected leaves may appear limp and the tips and margins hang down as if wilted. They do not develop marginal necrotic lesions nor do the margins become excessively wavy or cupped up or down.

4.7.4.2 Problem Soils

Iron deficiency is likely to occur in:

- Alkaline soils whose levels of soluble Fe are low
- Waterlogged soils

- Acid soils with excessively high levels of soluble Mn, Zn, Cu, and Ni that depress Fe uptake by plants
- Sandy soils low in total Fe
- Peat and muck soils in which organic matter ties up Fe

4.7.4.3 Correcting Deficiency

While soil dressings of inorganic Fe salts such as iron sulfates or chlorides have corrected deficiencies in some soils, the applied Fe quickly becomes insoluble and less available to plants. Fe salts of various organic chelates are more promising as soil dressings because the chelate has the ability to keep Fe in solution. For acid soils, FeEDTA is the most effective chelate. FeHEDTA and FeDTPA are best on neutral soils and FeEDDHA is best on alkaline soils. However, large amounts of chelates may be required to be effective and may prove too costly.

An equally effective remedy is to apply solutions of inorganic salts or chelates to the foliage (1% solutions or 1 kg salt per 100 L water per ha). Because Fe is so immobile in plants, sprays may need to be applied every 10 to 15 days to provide Fe to new leaves. Advice on fertilizer practices used on similar soils in the district should be sought to obtain the best remedies for affected crops under local conditions.

4.7.5 Magnesium (Mg)

4.7.5.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Magnesium-deficient crops lack vigor and yield poorly. Affected plants are stunted and have short, thin stems and pale green foliage. Branching is severely affected and deficient plants are often single-stemmed The yields of lint and seed are much reduced as a result of the lower numbers of flowers and bolls produced.

Interveinal chlorosis on older leaves: Because Mg is readily transferred from old to young leaves, symptoms appear first and are more severe on old leaves, working up the plants to young leaves if the disorder persists. Pale green to yellow interveinal chlorosis develops on older leaves. The main and smaller veins remain green and prominent. Young leaves remain dark green and appear healthy.

Interveinal necrosis on older leaves: If a deficiency persists and becomes severe, small, pale brown necrotic lesions develop in the yellow interveinal areas in the bodies of leaves. Eventually, the necrotic lesions join together. They initially leave the veins green and unaffected. Finally, the veins are affected and the leaves die and fall.

4.7.5.2 Problem Soils

Magnesium deficiency is likely to occur in:

- Acid sandy soils from which Mg has been leached
- Strongly acid peat and muck soils whose total Mg is low
- Soils that have been over-fertilized with Ca (for example, lime) or K and whose Mg uptake is inhibited

4.7.5.3 Correcting Deficiency

Magnesium deficiency in acid soils is best corrected by broadcasting dolomite (a mixture of calcium and magnesium carbonates) and mixing it into the soil some months before sowing. When the problem is only Mg deficiency, band applications of magnesium sulfate or chloride at or before planting may be effective.

Tests can estimate the amounts of soluble and exchangeable Mg in the soil, and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Magnesium deficiency in existing crops can be corrected by applying soluble salts such as magnesium sulfate, chloride, or nitrate with irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to meet crop requirements.

4.7.6 Manganese (Mn)

4.7.6.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Manganese-deficient crops lack vigor and yield poorly. Affected crops may appear patchy. Plants in Mn-poor areas are stunted and have short, stout stems and dark to pale green foliage. Branching is reduced and few flowers and bolls are produced.

Interveinal chlorosis on younger leaves: Because Mn is not readily transferred from old to young leaves, symptoms appear first and are more severe on young leaves. Old leaves usually remain dark green and appear healthy. Young leaves are small, turn pale green, then develop faint yellow interveinal chlorosis that becomes more distinct if the deficiency persists. The veins remain green and easily seen. The margins of affected leaves cup down or roll beneath the leaves.

Brown necrotic lesions on younger leaves: When a deficiency becomes severe, small dark brown necrotic lesions develop within the chlorotic areas on young leaves. The surrounding tissue may become puckered and produce a distorted appearance.

4.7.6.2 Problem Soils

Manganese deficiency is likely to occur in:

- Strongly alkaline soils whose Mn is less available to plants
- Poorly drained, peaty soils in which Mn is tied up in less available forms
- Strongly acid, sandy soils from which soluble Mn has been leached by heavy rain
- Soils formed from rocks low in Mn

4.7.6.3 Correcting Deficiency

Foliar sprays and soil dressings of Mn salts and oxides have been used to correct deficiencies. Soil dressings are more effective when broadcast and mixed into soil some weeks before sowing. However, foliage applications are generally more successful. One or more foliar sprays of 0.5 to 1% solutions of soluble Mn salts (for 0.5 to 1 kg manganese sulfate per 100 L water per ha) usually correct the deficiency, the first applied 5 to 6 weeks after seedling emergence. If the symptoms reappear, the spray should be repeated immediately. While soil dressings usually last 5 to 6 years before fresh applications are needed, foliar sprays must be reapplied to every crop.

Tests can estimate the amount of available Mn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

4.7.7 Nitrogen (N)

4.7.7.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Nitrogen-deficient crops are unthrifty, lack vigor, and are slower to mature. Affected plants are stunted and have short, thin stems that often develop bright red pigmentation on the lower sections. Leaves are small, pale green to yellow, and often hang vertically and fold inward towards the stems. Branching is reduced and severely deficient plants

are usually single-stemmed. Flower production is reduced and immature bolls may be shed before maturity. As a result, yields of lint and seed are low.

Pale yellow older leaves: Because N is readily transferred from old to young leaves, symptoms develop first and are more severe on old leaves, working up the plants to young leaves if the disorder persists. Old leaves turn pale green, then pale yellow, and develop brown necrosis, usually in interveinal areas, before dying and falling. Young leaves are small and remain green.

4.7.7.2 Problem Soils

Nitrogen deficiency is likely to occur in:

- Sandy soils that have been leached by heavy rainfall or excessive irrigation
- Soils low in organic matter
- Soils with a long history of cropping, in which supplies of N are exhausted

However, even fertile soils may suffer temporary N deficiency when double-cropped, heavily leached, or waterlogged.

4.7.7.3 Correcting Deficiency

Nitrogen deficiency is corrected by increasing levels of available N in the soil by fallowing, which allows organic N to be converted to mineral N; by growing cover or cash crops of legumes, which can fix atmospheric N_2; or by adding nitrogenous fertilizers. Suitable fertilizers are urea, gaseous ammonia or ammonium sulfate, nitrate, and phosphates. Crop growth depends on the amount of nitrate (NO_3)-N already in the soil.

Tests can measure the amounts of total N and nitrate (NO_3)-N in the soil prior to sowing, and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Nitrogen deficiency in existing crops can be corrected by applying soluble salts, such as urea, with irrigation water or as a foliar spray. Spray applications usually result in a rapid response of short duration, and additional sprays 10 to 14 days apart may be needed to supply enough N for the crop.

4.7.8 Phosphorus (P)

4.7.8.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Phosphorus-deficient crops are unthrifty and yield poorly. Affected plants are very stunted and have short, thin stems which often have red-brown pigmentation on their lower sections. Leaves are small and dark green. Branching is reduced and severely deficient plants are often single-stemmed. Flower production is delayed and reduced. Because fewer bolls are set, yields of lint and seed are low.

Necrosis of older leaves: Because P is readily transferred from old to young leaves, symptoms appear first and are more severe on old leaves, working up the plants to young leaves if the deficiency persists. All leaves are small and dark green. Old leaves develop dull yellow chlorosis on the margins, which is rapidly followed by grey necrosis. The necrosis advances rapidly into interveinal areas, killing the leaves, which then readily fall.

4.7.8.2 Problem Soils

Phosphorus deficiency is likely to occur in:

- Soils low in organic matter
- Soils with a long history of cropping and exhausted P supplies

- Highly weathered, Fe-rich soils whose phosphate is fixed in less available forms
- Soils that have lost topsoil through erosion
- Alkaline soils whose P may be tied up in insoluble phosphates that are less available to plants

4.7.8.3 Correcting Deficiency

Phosphorus deficiency can be corrected by applying phosphatic fertilizers to the soil at or before sowing. Suitable fertilizers are single or triple superphosphates or phosphates. The growth of crops depends on the amounts of water-soluble phosphates and the rates of exchange between soluble and insoluble forms of P compounds in the soil.

Tests can estimate the amount of available phosphate in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Phosphorus deficiency in existing crops can be corrected by applying soluble salts, such as ammonium phosphates, with irrigation water. Spray applications of similar salts are usually not recommended because of the large number needed to supply crop requirements.

4.7.9 Potassium (K)

4.7.9.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Potassium-deficient crops are unthrifty, mature slowly, and yield less. Affected plants are stunted and have short, thin stems, and small green leaves. Branching is reduced and fewer flowers and bolls are produced. Yields of lint and seed are much reduced.

Interveinal chlorosis of older leaves: Because K is readily transferred from old to young leaves, symptoms develop first and are more severe on old leaves. If the deficiency persists, the symptoms advance up the plants to young leaves. They start with blotchy, pale yellow, interveinal chlorosis on old leaves. Young leaves remain dark green and appear healthy.

Marginal necrosis on older leaves: If a deficiency persists, pale brown or dark purple-brown necrosis develops on the margins of affected leaves. The lesions advance into interveinal areas and the margins of the leaves tend to cup downward. The major veins remain green and are easily seen.

Necrotic lesions on petioles: In severely deficient plants, necrotic lesions often develop on the petioles of affected older leaves.

4.7.9.2 Problem Soils

Potassium deficiency is likely to occur in:

- Soils low in organic matter after many years of cropping
- Sandy soils formed from parent material low in K
- Light textured soils from which K has been leached by heavy rainfall

4.7.9.3 Correcting Deficiency

Potassium deficiency is corrected by applying potassium nitrate, sulfate, or chloride to the soil at or before sowing. Crop yield depends on the amounts of water-soluble and exchangeable K in the soil. Tests can measure the amount of available K in the soil and predict the amount of fertilizer needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Potassium deficiency of existing crops can be corrected by applying soluble K salts, such as potassium sulfate, chloride, or nitrate, with irrigation water. The foliar application of similar salts is usually not recommended because of the large number of sprays needed to meet crop requirements.

4.7.10 Sulfur (S)

4.7.10.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Sulfur deficiency causes unthriftiness, lack of vigor, and poor yield. Affected plants are stunted and have short, thin stems and small, pale green to yellow leaves. Branching is reduced, fewer flowers are produced, and fewer bolls set. As a result, yields of lint and seed are reduced.

Pale yellow younger leaves: Because S is not readily transferred from old to young leaves, symptoms develop first and are more severe on young leaves. They begin when entire plants turn pale green. The youngest leaves then develop general pale yellow chlorosis that includes the veins. If the deficiency persists and becomes severe, pale brown necrotic lesions may develop in tissues adjacent to the margins of affected leaves. In addition, the margins often become excessively wavy or cupped upward. Old leaves remain pale green and do not develop marginal symptoms.

4.7.10.2 Problem Soils

Sulfur deficiency is likely to occur in:

- Soils low in organic matter after many years of cropping
- Soils formed from parent material low in S (for example, some volcanic rocks and ash)
- Acid sandy soils from which sulfates have been leached

4.7.10.3 Correcting Deficiency

The application of soil dressings of any S fertilizer will correct a deficiency. On alkaline soils, elemental S (flowers of sulfur) may be broadcast and thoroughly mixed into the soil about 4 months before sowing. On neutral or acid soils, gypsum (calcium sulfate) is a useful source of S.

Tests can measure the amount of available sulfate in the soil before sowing and predict the amount of fertilizer required. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

Sulfur deficiency in existing crops can be corrected by applying soluble sulfate salts, such as magnesium, ammonium, or potassium sulfate, in irrigation water. Foliar sprays of similar salts are usually not recommended because of the large number of applications needed to supply crop requirements.

4.7.11 Zinc (Zn)

4.7.11.1 Deficiency Symptoms

Unthrifty, low-yielding crops: Zinc-deficient crops lack vigor and are unthrifty. Areas of poor growth may occur adjacent to healthy, apparently normal plants, giving the crop a patchy appearance. Plants in Zn-poor areas are stunted and have short, thin stems. Leaves are smaller than usual and may be dark or pale green, with or without brown necrotic lesions. Branching is reduced and fewer flowers and bolls are set. As a result, yields of lint and seed are low.

Brown necrotic lesions on older leaves: In young plants, symptoms appear as dark brown necrotic lesions in interveinal areas of the cotyledons and older true leaves. These lesions develop without prior chlorosis and initially do not affect the veins. The margins of affected leaves often cup upward. Eventually, the lesions join together and affect the veins, killing the leaves, which then fall.

Chlorosis and malformation of younger leaves: If a deficiency persists, pale yellow, blotchy chlorosis develops on young leaves. The youngest leaves do not grow and are often malformed and have holes or torn margins. By this stage, the youngest internodes are very short and the plant has a bushy appearance. The malformed leaves form rosettes at the tops of the shoots.

4.7.11.2 Problem Soils

Zinc deficiency is likely to occur in:

- Strongly alkaline soils whose availability of Zn is depressed
- Leached sandy soils whose total Zn is low
- Leveled soils whose Zn-deficient subsoils may be exposed on the surface
- Soils in which heavy frequent applications of phosphatic fertilizers may have reduced the use of Zn by crops

4.7.11.3 Correcting Deficiency

Foliage and soil applications of Zn salts have been used to correct deficiencies. Soil dressings of Zn chelates, sulfates or oxides should be broadcast and mixed into the soil 2 to 3 months before sowing. Soil-applied Zn lasts 6 to 8 years before fresh applications are needed, but foliar sprays have no residual effects and fresh applications must be made to each crop. The best results from foliar sprays are obtained when a 0.5 to 1% solution of a soluble Zn salt (for example, 0.5 to 1 kg zinc sulfate heptahydrate per 100 L water per ha) is applied 2 to 3 weeks after seedling emergence. Additional sprays should be applied as soon as symptoms reappear.

Tests can estimate the amount of available Zn in a soil and predict whether fertilizer is needed. The best prediction can be obtained by seeking advice on fertilizer practices used on similar soils in the district.

4.8 SALINITY AND TOXICITY[2]

4.8.1 Toxicity Symptoms

Unthrifty, low-yielding crops: Excess sodium chloride (NaCl) in soils causes a lack of vigor, poor yields or lint and seed, and unthriftiness. Affected plants are stunted and have short stems that may develop red pigmentation if the toxicity persists for a long time. Leaves are dark green, often much smaller than usual, and have a harsh appearance. If the toxicity is mild and persists for some time, the leaves may be held vertically and point downward to produce a wilted appearance.

Necrosis on older leaves: Excess sodium chloride accumulates in older tissues. Therefore, symptoms appear first and are more severe on old leaves. If the toxicity develops slowly over time, small, purple-brown lesions appear on the margins of older leaves and advance into interveinal areas as the toxicity progresses. Eventually, small, grey necrotic lesions appear in interveinal areas.

Similar grey necrotic lesions represent the first symptom when toxicity develops rapidly, perhaps as a result of irrigation or flooding with very saline water. The grey lesions join and eventually all interveinal tissues die, leaving the major veins green. The leaves then die and fall.

4.8.2 Problem Soils

Sodium chloride toxicity is more likely to occur in:

- Saline soils formed from salt-water sediments
- Previously fertile soils that were flooded or heavily irrigated with water containing high concentrations of NaCl

4.8.3 Correcting Toxicity

Leaching with good quality irrigation water is the most effective means of removing excess Na or Cl from soil. The water table may have to be lowered. Permeable soils such as well structured

sandy soils are often easily reclaimed, but the problem is more difficult in less permeable soils (for example, poorly structured heavy clays).

If exchangeable Na in the soil is high, reclamation involves replacing the adsorbed Na with Ca by applying gypsum (calcium sulfate) and leaching the dissolved Na and Cl beyond the rooting depths of the plants. If irrigation water is to be used to leach the Na, its quality should be checked before use to make sure it is not saline. Where excess NaCl cannot be wholly corrected by soil leaching, a more tolerant species may have to be grown.

4.9 WEIGHTS AND MEASURES

Conversion Factor — One bushel of ginned cotton is approximately equal to 3.26 lb seed cotton including trash.

TABLE 4.12
Cotton Seeds/lb, Weight/bu, and Germination Time

Seeds/lb (1,000)	Seeds/g (no.)	Weight/bu (lb)	Germination Time (days)
4	8	—	12

TABLE 4.13
Cotton Weights and Measures

	Approximate Net Weight		
Commodity	**Unit**	**lb**	**kg**
Cotton	bale, gross	500	227
	bale, net	480	218
Cottonseed	bushel	32	14.5
Cottonseed oil	gallon	7.7	3.5

Source: U.S. Department of Agriculture, *Agricultural Statistics, 2001*, U.S. Government Printing Office, Washington, D.C.

REFERENCES

1. Smith, C.W., *Crop Production: Evolution, History, and Technology*, 1995, John Wiley & Sons, New York.
2. Grundon, N.J., *Hungry Crops: A Guide to Nutrient Deficiencies in Field Crops*, 1987, Queensland Department of Primary Industries, Brisbane, Australia.

5 Sugar Beet (*Beta vulgaris* L. spp.)

5.1 INTRODUCTION

The sugar beet belongs to the Chenopodiaceae (goosefoot) family. It is known as betterave a sucre in French, remolacha azucar in Spanish, barbabietola zucchero in Italian, and zuckerruebe in German.

Sugar beets grow best in regions that have sunny days and cool nights. They require slightly acid to neutral soils (pH 5.8 to 7.0) and high water requirements. They are frequently grown under irrigation. The enlarged portion of the root is called the beet. It normally weighs 1-1/2 to 3 lb and has a tap root extending to soil depths of 2 to 5 feet. The sugar (sucrose) content of a beet ranges from 15 to 20% of fresh weight. Sugar content is affected by climate. Near-harvest moisture stress increases percent of beet sugar content. Fertility (nitrogen) stress increases beet sugar content. It takes about 1.07 tons of raw sugar to produce 1 ton of refined sugar.

The primary beet-growing states are California, Idaho, Michigan, Minnesota, and North Dakota. Oregon in the leading producer of sugar beet seeds.

5.2 PRODUCTION STATISTICS

TABLE 5.1
U.S. Harvested Acreage, Yield, and Production, 1991–2000

Year	Harvested Acres (1,000)	Yield (tons/acre)	Production (1,000 tons)
1991	1,366.7	20.3	26,203
1992	1,411.5	20.6	29,143
1993	1,409.4	18.6	26,249
1994	1,443.0	22.1	31,653
1995	1,420.1	19.8	26,065
1996	1,323.3	20.2	26,680
1997	1,428.3	20.9	29,686
1998	1,450.7	22.4	32,499
1999	1,527.3	21.9	33,420
2000[a]	1,378.1	23.6	32,521

[a] Preliminary.

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

TABLE 5.2
U.S. Acreage, Yield, and Production by Leading States, 2000

State	Area Harvested (1,000 acres)	Yield (tons/acre)	Production (1,000 tons)
Minnesota	430	21.5	9,245
North Dakota	232	22.1	5,127
Idaho	195	29.2	5,694
Michigan	166	20.5	3,403
California	93.5	32.5	3,039
U.S. Total	1,378.3	23.6	32,521

Source: National Agriculture Statistics Service, Washington, D.C.

TABLE 5.3
Leading Sugar Beet-Growing Countries[a]

Country	Short Tons of Sugar Beets (× 1,000)
France	34,756
Ukraine	34,447
Germany	38,732
Russia	28,135
U.S.	27,789
Turkey	16,915
China	14,975
Italy	14,677
U.K.	10,080

[a] Figures represent 2-year average, 1992–1993.

Source: United Nations Food and Agriculture Organization, Rome.

5.3 NUTRIENT ELEMENT REMOVAL AND UTILIZATION

TABLE 5.4
Average Nutrient Element Removal by a 10-Ton Sugar Beet plus Foliage Crop

Element	kg
Nitrogen	40–50
Phosphorus as phosphate	15–20
Potassium as potash	45–70
Magnesium as oxide	12–15
Sulfur	5

TABLE 5.5
Variations of Nutrient Element Removal by Sugar Beets Depending on Cultivation Intensity

			Nutrient Element (kg/ha)				
Intensity	Yield (tons/ha)	Beets/ha	Nitrogen	Phosphorus	Potassium	Magnesium	Sulfur
Low	20	30,000	100	40	160	28	10
Medium	40	50,000	180	64	240	50	18
High	60	75,000	240	90	300	72	24

Source: *IFA World Fertilizer Use Manual*, 2000, International Fertilizer Industry Association, Paris.

TABLE 5.6
Nutrient Element Utilization by a 30-Ton/Acre Sugar Beet Crop

Nutrient Element	Amount (lb/acre)
Nitrogen	255
Phosphorus as phosphate	40
Potassium as potash	550
Magnesium	80
Sulfur	45

5.4 PLANT ANALYSIS GUIDE

TABLE 5.7
Sugar Beet Plant Analysis

		Concentration of Element[a]		
Nutrient Element	**Plant Part**	**Critical Value, Field Sample[b,c]**	**Range Showing Deficiency Symptoms[d]**	**Range without Deficiency Symptoms[e]**
Boron	Blade	21	12–40	35–200
Calcium	Petiole	1 g/kg	0.4–10 g/kg	2–25 g/kg
	Blade	5 g/kg	1–4 g/kg	4–15 g/kg
Chlorine	Petiole	4 g/kg	0.1–0.4 g/kg	8–85 g/kg
Copper	Blade	—	<2	<2
Iron	Blade	55	20–55	60–140
Magnesium	Petiole	—	0.1–0.3 g/kg	1–7 g/kg
	Blade	—	0.25–0.5 g/kg	1–25 g/kg
Manganese	Blade	10	4–20	25–360
Molybdenum	Blade	—	0.01–0.15	0.20–20.0
Nitrogen (NO_3-N)	Petiole	1,000	70–500	350–35,000
	Storage root	1,000	70–500	800–4,000
Phosphorus ($H_2PO_4^-$-P)	Petiole	750	150–400	750–4,000
	Blade	—	250–700	1,000–8,000
	Seedling			
	Petiole	1,500	500–1,300	1,600–5,000
	Blade	3,000	500–1,700	3,500–14,000
	Cotyledon	1,500	200–700	1,600–13,000
Potassium (Na >1.5%)	Petiole	10 g/kg	2–6 g/kg	10–110 g/kg
	Blade	10 g/kg	3–6 g/kg	10–60 g/kg
Potassium (Na <1.5%)	Petiole[f]	—	5–20 g/kg	25–90 g/kg
	Blade	10 g/kg	4–5 g/kg	10–60 g/kg
Sodium	Petiole	—	—	0.2–90 g/kg
	Blade	—	—	0.2–37 g/kg
Sulfur (SO_4^{2-}-S)	Blade	250	50–200	500–14,000
Zinc	Blade	9	2–13	10–80

[a] All concentrations are on a dry weight basis and are noted as mg/g (ppm) except when noted as g/kg; $(g/kg)10^{-1} = \%$.
[b] Critical concentration is nutrient element concentration at which plant growth begins to decrease in comparison with plants above the critical concentration.
[c] All critical concentrations except for P in seedlings and N in roots are based on a sample of leaves that just fully expanded.
[d] Leaf material for chemical analysis must be collected shortly after appearance of leaf symptoms; otherwise, deficient plants may accumulate nutrients in leaves without restoring chlorotic tissues to normal. Use a color atlas to identify what deficiency, if any, occurred.
[e] The upper value reported is the highest observed to date for normal plants. Abnormally high values are often associated with other nutrient deficiencies; for example, blades low in Fe may contain up to 40 g Ca/kg.
[f] Because of the influence of Na on K content of petioles, blades must be used for K analysis when petioles contain <15 g Na/kg.

Source: *Soil Testing and Plant Analysis*, 3rd ed., Soil Science Society of America, Madison, WI.

Part II

Soil Classifications and Physical Characteristics

6 Major Soil Classification Systems

6.1 INTRODUCTION

Scientists of the U.S. Department of Agriculture (USDA) first proposed a soil classification scheme. The original classification scheme was published in 1949 with the somewhat cryptic designation of "first approximation." The system was refined through six succeeding approximations after distribution to soil scientists throughout the U.S. The seventh approximation was considered satisfactory.

Soil classification is defined as the "systematic arrangement of soils into groups or categories on the basis of their characteristics." Broad groupings are made on the basis of general characteristics and subdivisions on the basis of more detailed differences in specific properties.

6.2 SOIL TAXONOMY

A category is the aggregate of classes formed by differentiation within a population on a single basis. A category includes the entire population. It includes all classes differentiated on one basis. It is distinguished from a class, which is only one part of a category and is definable only in terms of the basis of differentiation. The higher categories of a hierarchy have fewer classes and they are more inclusive than the classes of the lower categories that include attributes from all the higher categories. Thus, high categorical levels are associated with high-level generalizations or abstractions. These abstractions are used as the bases of differentiation, but these ideas are expressed in terms of attributes assumed to be their consequences. Thus, soil attributes thought to be the results of such processes are the criteria used to segregate soils.

The definitions of categories, orders, series, and other terms, although not entirely clear, are intended to guide the selection and testing of properties and features used to characterize and classify soils. Soils thought to reflect processes or control processes are of great importance in this system. Although the processes of formation are influential in the selection of properties, the properties determine the placement of soils into classes. The applications of quantified definitions and observations are the tests of adequacy of the theories behind this model. Hence, soil taxonomy is considered a morphogenetic classification system.

6.2.1 Order

Classes at the order level are separated on the basis of properties resulting from the major processes and pathways of soil formation. Neither the genetic processes nor the courses of development are precisely known, but the accepted concepts influenced the selection of soil properties used to recognize and define the 12 classes currently considered. Many features are thought to have taken a long time to develop, are stable in a pedological sense, and are mainly static historically.

6.2.2 Suborder

Classes at the suborder level are separated within orders on the basis of soil properties that serve as major controls or reflect such controls on the current set of soil-forming processes. Most

properties selected, such as soil moisture regime or cold soil temperatures, are dynamic. Other properties, such as sand or alluvial sedimentation, relate to materials or processes that retard horizon development.

6.2.3 Great Group

Classes at the great group level are differentiated within suborders on the basis of properties that constitute subordinate or additional controls or reflect such controls on the current set of soil-forming processes. The properties selected, such as layers that retard percolation of water or root extension, are generally static, but some, such as moisture regime if not a criterion at the suborder level, are dynamic.

6.2.4 Subgroup

Classes at the subgroup level are differentiated within great groups on the basis of properties resulting from (1) blending or overlapping of sets of processes in space or time that causes one kind of soil to develop from or toward another kind of soil that has been recognized at the great group, suborder, or order level; or (2) sets of processes or conditions not recognized as criteria for any class at a higher level. A third kind of subgroup fits neither (1) nor (2) and is considered to typify the central concept of the great group.

6.2.5 Family

Classes at the family level are separated with subgroups on the basis of properties that reflect important conditions affecting behavior or potential for further change. Particle size, mineralogy, and soil depth are mainly capacity factors, whereas soil temperature and exchange activity are intensity factors.

6.2.6 Series

Classes at the series level are separated within families on the basis of properties that reflect relatively narrow ranges of soil-forming factors and processes that transform parent materials into soils. Some properties, such as coarse fragments, sand or silt content, color, and horizon thickness or expression, are indicative of parent materials. Others reflect influences on processes such as differences in intensity or amounts of precipitation and depth to the presence or concentration of soluble compounds.

6.3 SOIL ORDERS (U.S. SYSTEM OF SOIL TAXONOMY)[1]

Alfisols Mineral soils that have umbric or ochric epipedons and argillic horizons, and hold water at <1.5 MPa tension for at least 90 days when the soil is warm enough for plants to grow outdoors. Alfisols have a mean annual soil temperature of <8°C or a base saturation in the lower part of the argillic horizon of 35% or more when measured at pH 8.2.

Aridisols Mineral soils that have an aridic moisture regime, an ochric epipedon, and other pedogenic horizons, but no oxic horizon.

Entisols Mineral soils that have no distinct subsurface diagnostic horizons within 1 m of the soil surface.

Histosols Organic soils that have organic soil materials in more than half of the upper 80 cm, or are of any thickness if overlying rock or fragmental materials have interstices filled with organic soil materials.

Inceptisols Mineral soils that have one or more pedogenic horizons in which mineral materials other than carbonates or amorphous silica have been altered or removed but not accumulated to a significant degree. Under certain conditions, Inceptisols may have an ochric, umbric, histic, plaggen, or mollic epipedon. Water is available to plants more than half of the year or more than 90 consecutive days during a warm season.

Mollisols Mineral soils that have a mollic epipedon overlying mineral material with a base saturation of 50% or more when measured at pH 7. Mollisols may have an argillic, natric, albic, cambic, gypsic, calcic, or petrocalcic horizon, a histric epipedon or a duripan, but not an oxic or spodic horizon.

Oxisols Mineral soils that have an oxic horizon within 2 cm of the surface or plinthite as a continuous phase within 30 cm of the surface, and do not have a spodic or argillic horizon above the oxic horizon.

Spodosols Mineral soils that have a spodic horizon or a placic horizon that overlies a fragipan.

Ultisols Mineral soils that have an argillic horizon with a base saturation of <35% when measured at pH 8.2. Ultisols have a mean annual soil temperature of 8°C or higher.

Vertisols Mineral soils that have 30% or more clay, deep wide cracks when dry, and either gilgai micorelief intersecting slickensides, or wedge-shaped structural aggregates tilted at an angle from the horizon.

TABLE 6.1
Soil Order Prevalence

Soil Order	Area (km$^2 \times 10^3$)	Proportion (%)
Alfisols	12,621	9.6
Andisols	912	0.7
Aridisols	15,728	12.0
Entisols	21,137	16.2
Gelisols	11,260	8.6
Histisols	1,527	1.2
Inceptisols	12,850	9.8
Mollisols	9,006	6.9
Oxisols	9,810	7.5
Spodosols	3,354	2.5
Ultisols	11,054	8.3
Vertisols	3,160	2.4
Miscellaneous	18,398	14.0

TABLE 6.2
Soil Order Characteristics

Alfisols

Semi-arid to humid climates
Light colored surfaces
Subsoils rich in basic cations
Developed under deciduous forest vegetation in humid climates
Developed under grass or savannah vegetation in dry climates
Formed on a wide variety of parent materials
Found on all continents except Antarctica
Concentration in Northern Hemisphere, especially North America
Suborders: Aqualfs, Cryalfs, Ustalfs, Xeralfs, Udalfs

Andisols

Developed from volcanic ash, pumice, cinders, or other volcanic ejecta
Amorphous mineralogy
Low permanent and high variable charge
Low bulk density
High C and P content
Largest concentrations found around Pacific Ring of Fire
Suborders: Aquands, Cryands, Torrands, Xerands, Vitrands, Ustands, Udands

Aridisols

Do not have water available to mesophytic plants
Evapotranspiration exceeds precipitation
Low water-holding capacity
Shallow soil depth or restricted infiltration
Low osmotic potential due to salinity
Accumulation of soluble salts (gypsum and more soluble evaporites)
Calcium carbonate is present in all Aridisols
Occupy less than 50% of the arid land areas
Located in southwestern and central Asia, most of Australia, western North and South America, continental margins of Africa
Vegetation dominated by drought-escaping annual grasses, forbs, drought-enduring evergreen shrubs
Suborders: Cryids, Salids, Durids, Gypsids, Argids, Calcids, Cambids

Entisols

Formed in areas where pedogenesis has been present
Found in mountains, sand dunes, flood plains, coastal plains, and urban areas
Not defined by temperature or precipitation
Inherit many physical and chemical properties from parent materials
Suborders: Orthents, Psamments, Fluvents, Aquents, Arents

Gelisols

Permafrost-affected soils within 100 cm of the soil surface or gelic materials with 100 cm of the soil surface and permafrost within 200 cm of soil surface
Twelfth and newest soil order
Support unvegetated to continuously vegetated trunda
Suborders: Histels, Turbels, Orthels

Histosols

Formed from organic materials derived from plants
Formation is favored by wet or cold climates

TABLE 6.2 (CONTINUED)
Soil Order Characteristics

Contain a minimum of 12 to 18% organic C
Cation exchange capacity is high
Water retention closely related to degree of decomposition
Soil material has been used a fuel
Most occur in wetlands
Uniquely fragile and highly vulnerable to degradation
Largest expanses in west Siberian lowlands and Hudson's Bay lowlands of central Canada
Suborders: Folists, Fibrists, Saptists, Hemists

Inceptisols

Include soils that have undergone modification of parent material by structural development and alteration sufficient to differentiate from Entisols
Found in all known climates, subhumid to humid climates from equatorial to tundra regions
Order has inordinate diversity
Usually considered immature soils
Major soils on which agronomic crops are produced in some parts of the world
Suborders: Aquepts, Anthrepts, Cryepts, Ustepts, Xerepts, Udepts

Mollisols

Generally characterized as soils with thick, dark surface horizons resulting from organic C incorporation
Among the most important soils for food and fiber production
High levels of native fertility
Distributed throughout the mid-latitudes
Dark-colored soils of semiarid to subhumid grassland ecosystems
Clay mineralogy is typically dominated by 2:1 layer silicates
Relatively high soil organic matter (SOM) content conductive to the formation of water-stable aggregates
Suborders: Albolls, Aquolls, Rendolls, Cryolls, Xerolls, Ustolls, Udolls

Oxisols

Deep red, highly weathered soils confined almost exclusively to the tropics
Most are in areas with mean annual air temperatures >15°C
Humification occurs in all Oxisols
Textures may vary from sandy loam to clay
Gibbsite is present as a secondary mineral; the other frequent mineral is goethite
Have low nutrient retention capacity, anion adsoprtion, Ca deficiency, and Mn and Al toxicity
Support the largest areas of tropical forests
Suborders: Aquox, Torrox, Ustox, Perox

Spodosols

Most are sandy soils with relatively low water-holding capacities
Found on all continents, most in cool, humid climates
Formed under coniferous or deciduous forests but not under prairie vegetation
Droughty and infertile; require high inputs, especially P
Suborders: Aquods, Cryods, Humods, Orthods

Ultisols

Found on a variety of parent materials and under a range of climatic conditions
About 80% are in tropical regions, under many tropical and subtropical ecosystems
Found on almost all landforms
Common but minor mineral component is gibbsite

continued

TABLE 6.2 (CONTINUED)
Soil Order Characteristics

Extensively weathered, low base saturation, and low native fertility
Suborders: Aquults, Humults, Udults, Ustults, Xerults

Vertisols

Clay soils that exhibit impressive volume changes due to shrinking and swelling processes
Derived from a wide variety of parent materials
Natural vegetation is typically grassland and savanna
Dark colored; commonly lack distinct horizonation; finely textured
Neutral to alkaline in reaction
Exhibit high moisture retention characteristics
Highly productive
Suborders: Aquerts, Cryerts, Xererts, Torrerts, Uderts, Usterts

TABLE 6.3
Soil Orders Found in Different Temperature Regions

	Soil Temperature Regimes[a] (%)			
Order	**Tropical**	**Temperate**	**Boreal**	**Tundra**
Alfisols	38	39	23	0
Andisols	49	23	28	0
Aridisols	12	74	14	1
Entisols	28	68	4	0
Gelisols	0	0	0	100
Histisols	21	8	71	0
Inceptisols	47	42	11	0
Mollisols	4	50	46	0
Oxisols	98	2	0	0
Spodosols	« 1	18	82	0
Ultisols	69	31	1	0
Vertisols	47	52	1	0

[a] *Soil Taxonomy.* Soil Survey Staff, 1998, http://www.statlab.iastate.edu//soils/soildiv
Tropical: isomesic, isothermic, and isohyperthermic (MAST >8°C in which the difference in mean summer and mean winter temperature is < 6°C at 50-cm soil depth).
Temperate: mesic, thermic, and hyperthermic (MAST is >8°C at 50-cm soil depth).
Boreal: frigid, isofrigid, and cytic (MAST is 0–8°C at 50-cm soil depth).
Tundra: pergelic (MAST <0°C at 50-cm soil depth).

Source: Modified from data supplied through USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.

TABLE 6.4
Soil Orders, Characteristics, and Diagnoses

Order	Characteristic	Diagnosis	World Area [million mi^2 (%)]
Entisol	Recent	Lack of discernible horizons	6.5 (12)
Inceptisol	Young	Horizons present but poorly developed	8.1 (16)
Vertisol	Inverted	Cracks; all horizons have high clay content	1.1 (2.2)
Aridisol	Arid climate	Prominent calcic horizon	9.9 (19.7)
Mollisol	Soft, rich	Prominent mollic horizon	4.6 (9.2)
Spodosol	High ash content	Prominent spodic horizon	2.8 (5.6)
Alfisol	High clay content	Prominent argillic horizon; ochric horizon	7.6 (15.1)
Ultisol	Heavily leached	Aall horizons heavily weathered; argillic horizon present	4.4 (8.8)
Oxisol	High oxide content	Prominent oxic horizon; forms laterite	4.8 (9.6)
Histosol	High organic content	Prominent histic horizon (peat)	0.4 (0.8)

TABLE 6.5
Areas and Percentages of Suborders and Miscellaneous Land Units Based on Ice-Free Land Area

Suborder	Area (km^2 × 10^3)	Percentage
	Alfisols	
Aqualfs	836	0.7
Cryalfs	2,518	1.9
Ustalfs	5,664	4.3
Xeralfs	897	0.7
Udalfs	2,706	0.2
Subtotal	12,621	9.6
	Andisols	
Cryands	255	0.2
Torrands	2	0.1
Xerands	32	«0.1
Vitrands	281	0.2
Ustands	63	0.1
Udands	279	0.2
Subtotal	912	0.7
	Aridisols	
Cryids	943	0.7
Salids	890	0.7
Gypsids	683	0.5
Argids	5,408	4.1
Calcids	4,873	3.7
Cambids	2,931	2.3
Subtotal	15,728	12.0
	Entisols	
Aquents	116	0.1
Psamments	4,428	3.4

continued

TABLE 6.5 (CONTINUED)
Areas and Percentages of Suborders and Miscellaneous Land Units Based on Ice-Free Land Area

Suborder	Area (km^2 × 10^3)	Percentage
Fluvents	2,860	2.2
Orthents	13,733	10.5
Subtotal	21,137	16.2
	Gelisols	
Histels	1,013	0.8
Turbels	6,333	4.8
Haplels	3,914	3.0
Subtotal	11,260	8.6
	Histosols	
Folists	«1	«0.1
Fibrists	197	0.1
Hemists	988	0.8
Saprists	341	0.3
Subtotal	1,527	1.2
	Inceptisols	
Aquepts	3,199	2.5
Anthrepts	<1	«0.1
Cryepts	457	0.3
Ustepts	4,241	3.2
Xerepts	685	0.5
Undepts	4,247	3.3
Subtotal	12,830	9.8
	Mollisols	
Albolls	28	«0.1
Aquolls	118	0.1
Rendolls	266	0.2
Xerolls	924	0.7
Cryolls	1,164	0.9
Ustolls	5,245	4.0
Udolls	1,261	1.0
Subtotal	9,006	6.9
	Oxisols	
Aquox	320	0.2
Torrox	31	«0.1
Ustox	3,096	2.4
Perox	1,162	0.9
Udox	5,201	4.0
Subtotal	9,810	7.5

TABLE 6.5 (CONTINUED)
Areas and Percentages of Suborders and Miscellaneous Land Units Based on Ice-Free Land Area

Suborder	Area ($km^2 \times 10^3$)	Percentage
	Spodosols	
Aquods	169	0.1
Cryods	2,460	1.9
Humods	58	<0.1
Orthods	667	0.5
Subtotal	3,354	2.5
	Ultisols	
Aquults	1,281	1.0
Humults	344	0.3
Udults	5,540	4.2
Ustults	3,870	3.0
Xerults	19	«0.1
Subtotal	11,054	8.5
	Vertisols	
Aquerts	5	«0.1
Cryerts	15	«0.1
Xererts	99	0.1
Torrerts	889	0.7
Usterts	1,768	1.3
Uderts	384	0.3
Subtotal	3,160	2.4
	Miscellaneous	
Shifting	13,076	10.0
Other	5,322	4.0
Subtotal	18,398	14.0
Grand Total	130,797	100.0

Source: USDA-NRCS, Washington, D.C., 1998.

TABLE 6.6
Prefixes and Connotations for Great Group Names in the U.S. Soil Classification System

Prefix	Connotation	Prefix	Connotation
acr	Extreme weathering	luv	Illuvial
agr	Agric horizon	med	Of temperate climates
alb	Albic horizon	nadur	See *natr* and *dur*
and	Ando-like	natr	Presence of natric horizon
anthr	Anthropic epipedon	ochr	Presence of ochric epipedon
arg	Argillic horizon	pale	Old development
bor	Cool	pell	Low chroma
cale	Calcic horizon	plae	Presence of a thin cemented layer
camb	Cambic horizon	plag	Presence of plaggen horizon
chrom	High chroma	plinth	Presence of plinthite
cry	Cold	psamm	Sand texture
dur	Duripan	quartz	High quartz content
dystr, dys	Low base saturation	rhod	Dark red color
cutr, eu	High base saturation	sal	Presence of salic horizon
fen	Presence of iron	sider	Presence of free iron oxides
fluv	Floodplain	sombr	Dark horizon
frag	Presence of fragipan	sphagn	Presence of Sphagnum moss
fraglost	See *frag* and *glots*	sulf	Presence of sulfides or their oxidation products
gibbs	Presence of gibbsite	tort	Torric moisture regime
glots	Tongued	trap	Continually warm and humid
gyps	Presence of gypsic horizon	ud	Udic moisture regime
hal	Salty	umbr	Presence of umbric epipedon
hapl	Minimum horizon	ust	Ustic moisture regime
hum	Presence of humus	verm	Wormy or mixed by animals
hydr	Presence of water	vitr	Presence of glass
kand	Presence of low activity clay	xer	Xeric moisture regime

TABLE 6.7
U.S. Soil Classification System

Order	Suborder	Great Group
Alfisols	Aqualfs	Albaqualfs
	Duraquaifs	
	Fragiaqualfs	
	Glossaqualfs	
	Kandiaqualfs	
	Natraqualfs	
	Ochraqualfs	
	Plinthaqualfs	
	Umbraqualfs	
	Boralfs	Cryoboralfs
	Eutroboralfs	
	Fragiboralfs	
	Glossoboralfs	
	Natriboralfs	
	Palehoralfs	
	Udalfs	Agrudalfs
	Ferrudalfs	
	Fragiudalfs	
	Fraglossudalfs	
	Glossudalfs	
	Hapludalfs	
	Kandiudalfs	
	Kanhapludalfs	
	Natrudalfs	
	Paleudalfs	
	Rhodudalfs	
	Ustalfs	Durustalfs
	Haplustalfs	
	Kandiustalfs	
	Kaofiapiustalfs	
	Natrustalfs	
	Paleustalfs	
	Plinthustalfs	
	Rhodustalfs	
	Xeralfs	Durixeralfs
	Fragixeralfs	
	Haploxeralfs	
	Natrixeralfs	
	Palexerralfs	
	Plinthoxeralfs	
	Rhodoxeralfs	
Aridisols	Argids	Durargids
	Haplargids	
	Nadurargids	
	Natrargids	
	Paleargids	
	Orthids	Calciorthids
	Camnorthids	

continued

TABLE 6.7 (CONTINUED)
U.S. Soil Classification System

Order	Suborder	Great Group
	Durorthids	
	Gypsiorthids	
	Paieorthids	
	Salorthids	
Entisols	Aquents	Cryaquents
	Fluvaquents	
	Haplaquents	
	Hydraquents	
	Psammaquents	
	Sulfaquents	
	Tropaquents	
	Arents	Arents
	Fluvents	Cryofluvents
	Torrifluvents	
	Tropofluvents	
	Udifluvents	
	Ustifluvents	
	Xerofluvents	
	Orthents	Cryorthents
	Torriorthents	
	Troporthents	
	Udorthents	
	Ustorthents	
	Xerorthents	
	Psamments	Cryopsamments
	Quartzipsamments	
	Torripsamments	
	Tropopsamments	
	Udipsamments	
	Ustipsamments	
	Xeropsamments	
Histosols	Fibrists	Borofibrists
	Cryofibrists	
	Luvifibrists	
	Medifibrists	
	Tropofibrists	
	Folists	Borofolists

6.4 GLOBAL DISTRIBUTION OF MAJOR SOIL ORDERS

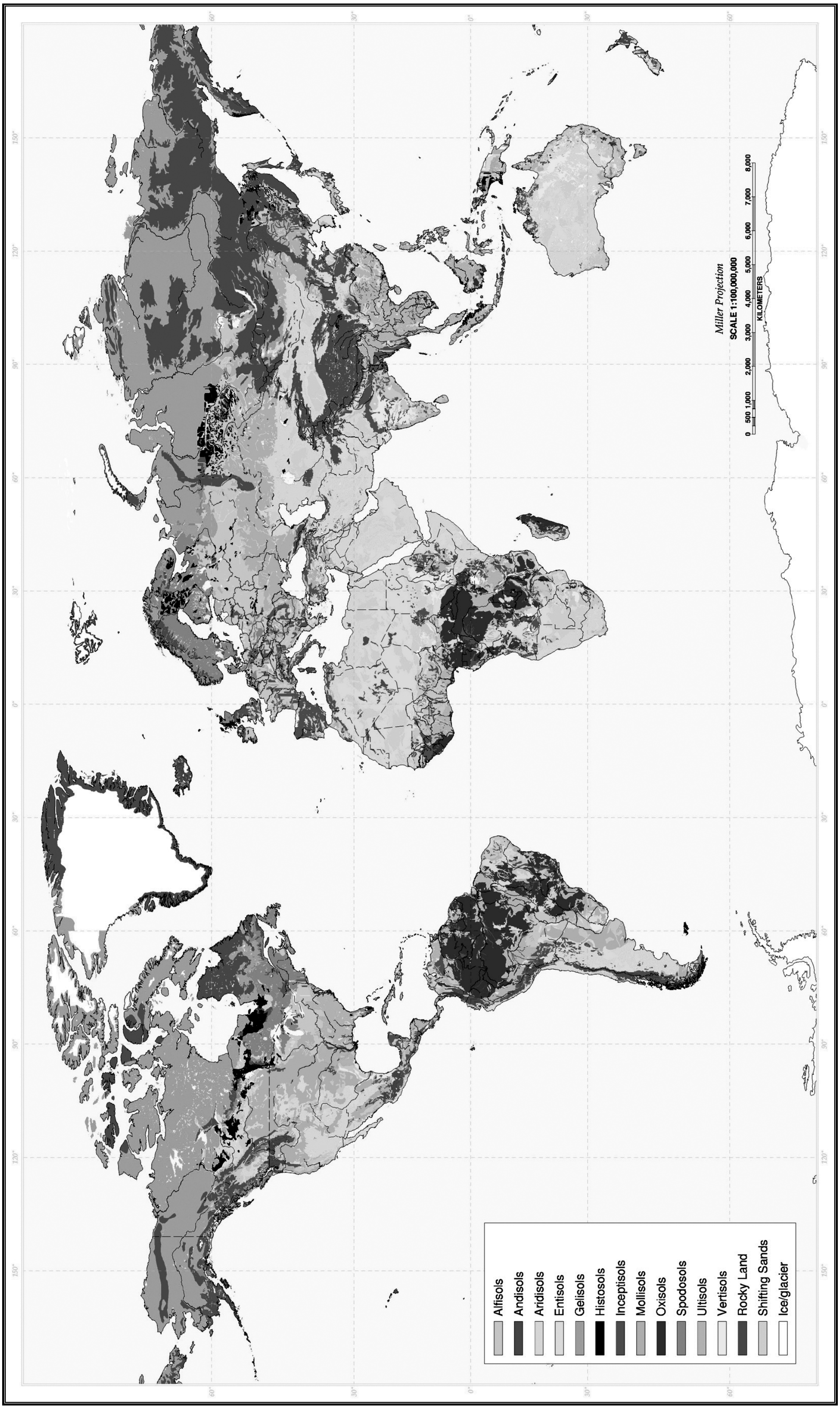


FIGURE 6.1 Proportions of Earth's surface occupied by the great soil zones. (*Source*: Hanson, A.A., 1990, *Practical Handbook of Agricultural Science*, CRC Press, Inc., Boca Raton, FL. With permission.)

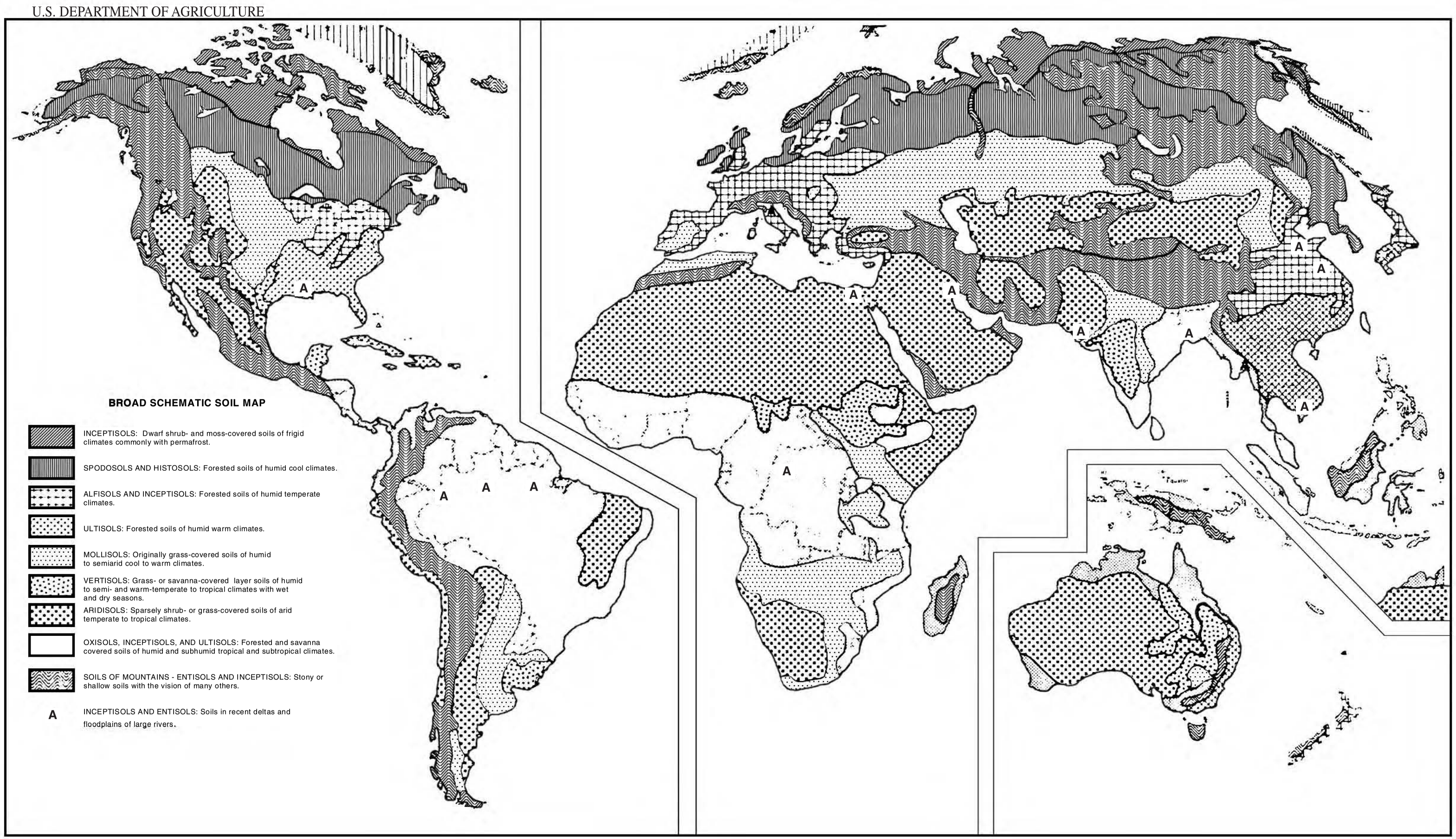


FIGURE 6.2 Map showing nine major soil regions. Proportions of the land surface: Inceptisols, 3.44%; Spodosols and Histosols, 9.89%; Alfisols and Inceptisols, 4.25%; Ultisols, 3.83%; Mollisols, 12.38%; Vertisols, 2.81%; Aridisols, 25.34%; Oxisols, Inceptisols, and Ultisols, 20.54%; Entisols and Inceptisols (mountain soils), 17.44%.

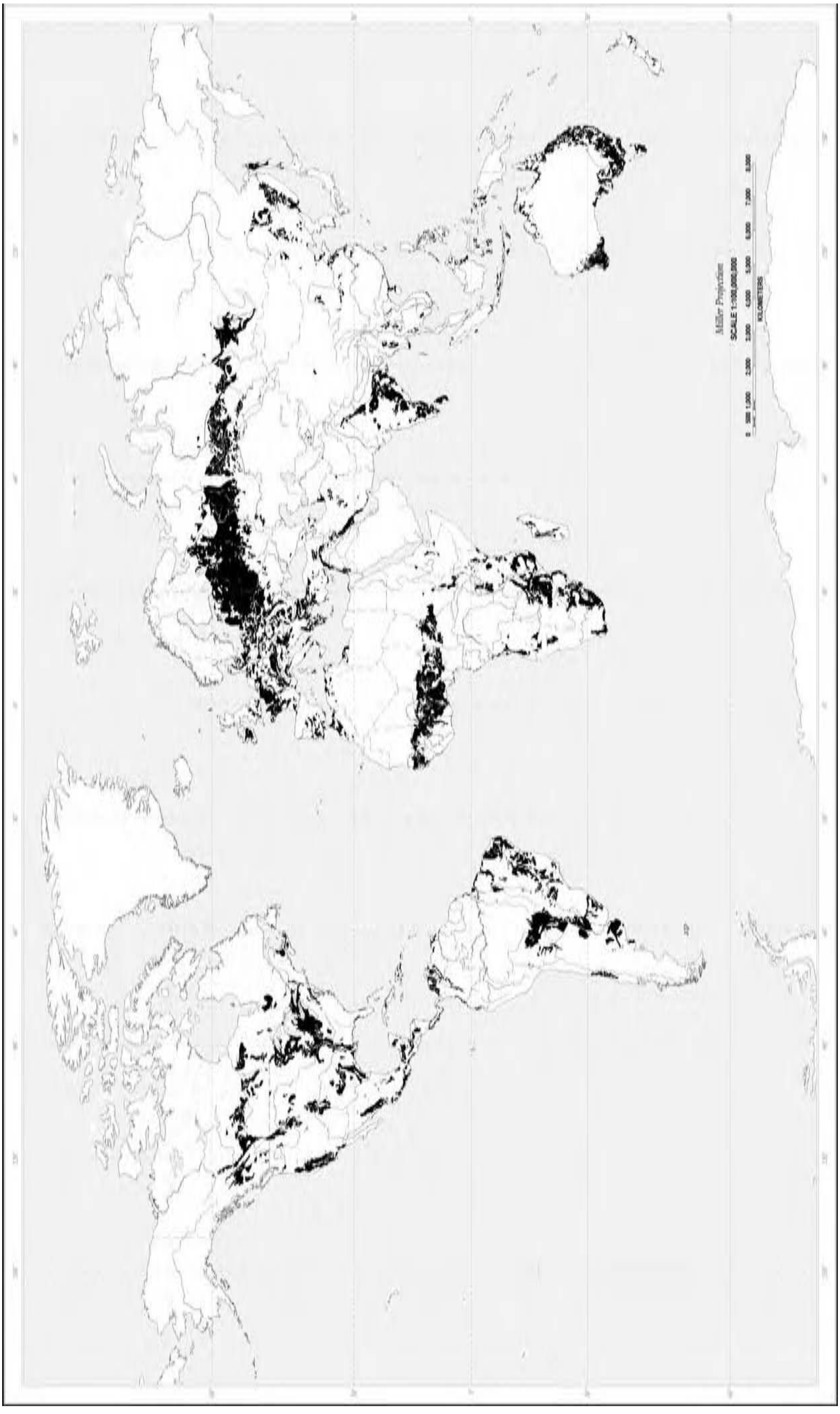


FIGURE 6.3 Global distribution of Alfisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

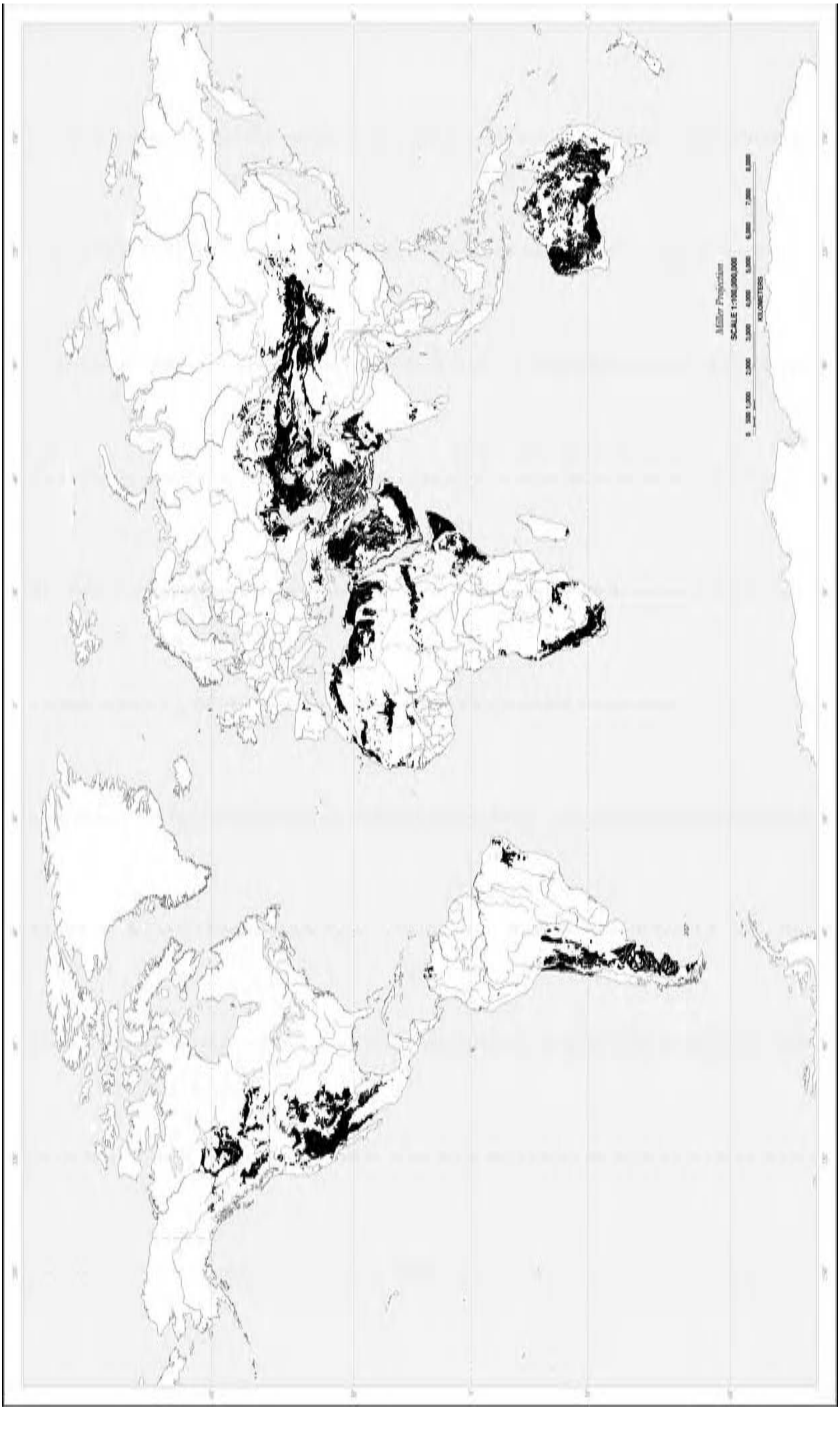


FIGURE 6.4 Global distribution of Aridisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

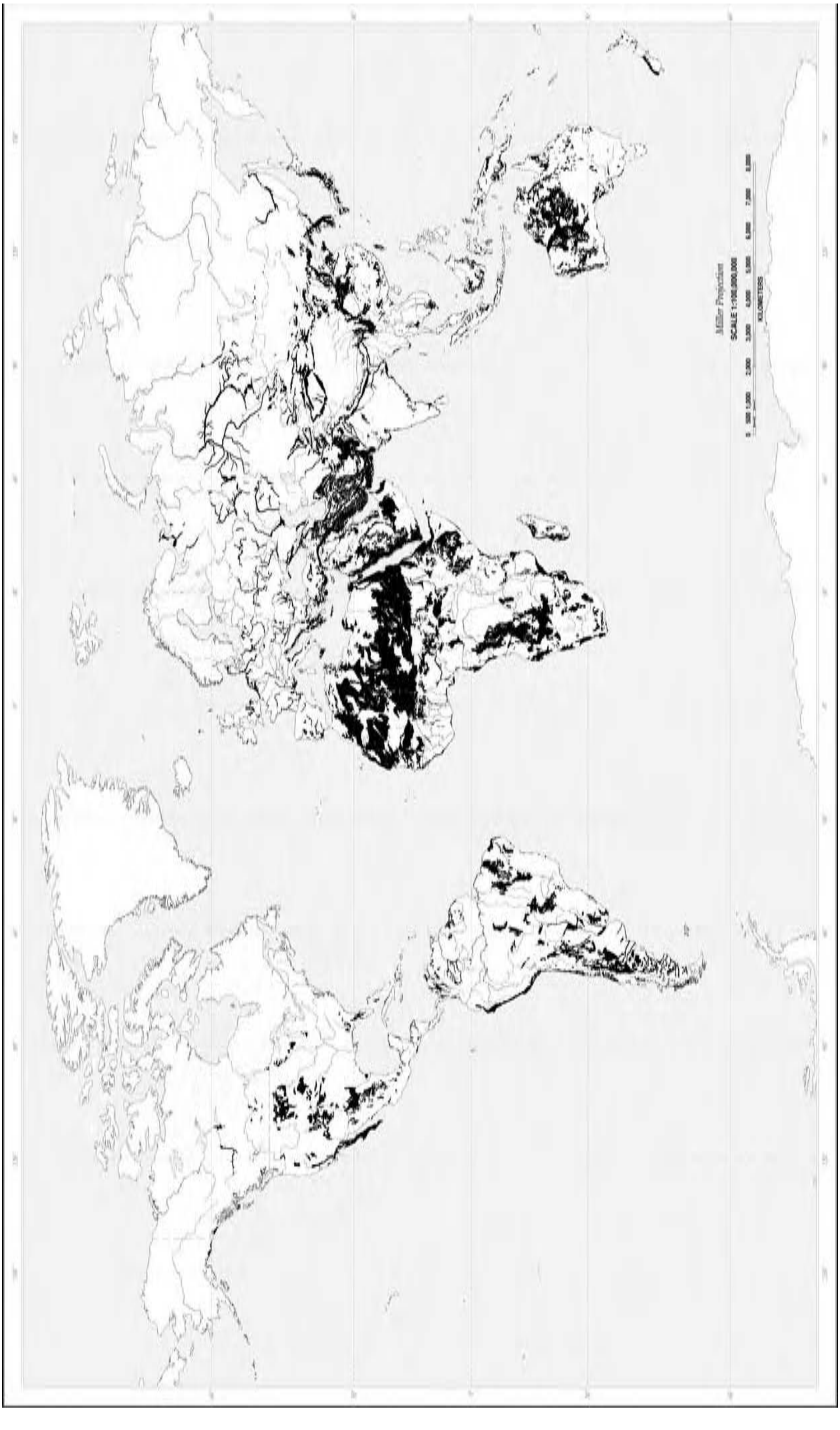


FIGURE 6.5 Global distribution of Entisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

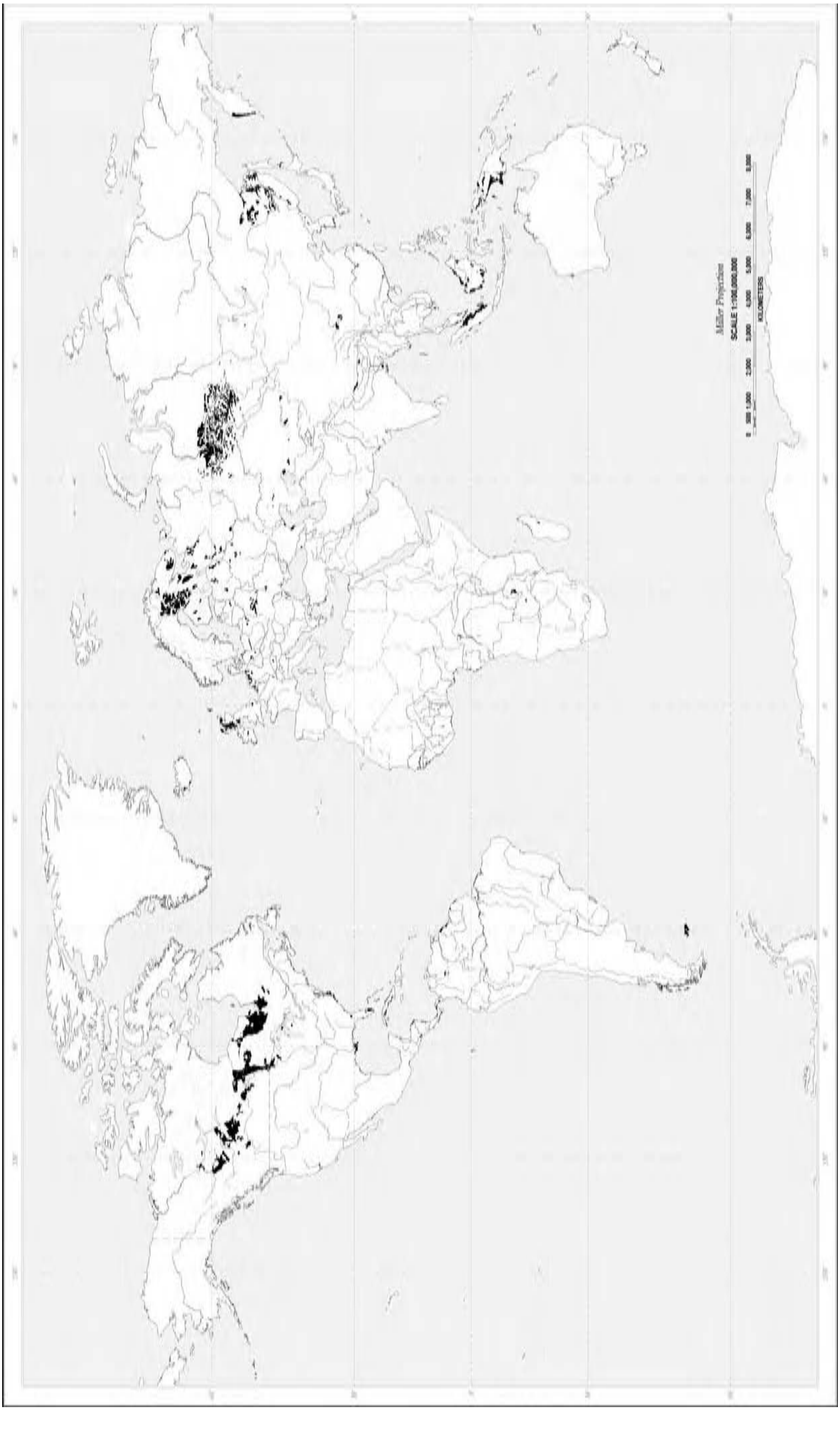


FIGURE 6.6 Global distribution of Histosols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

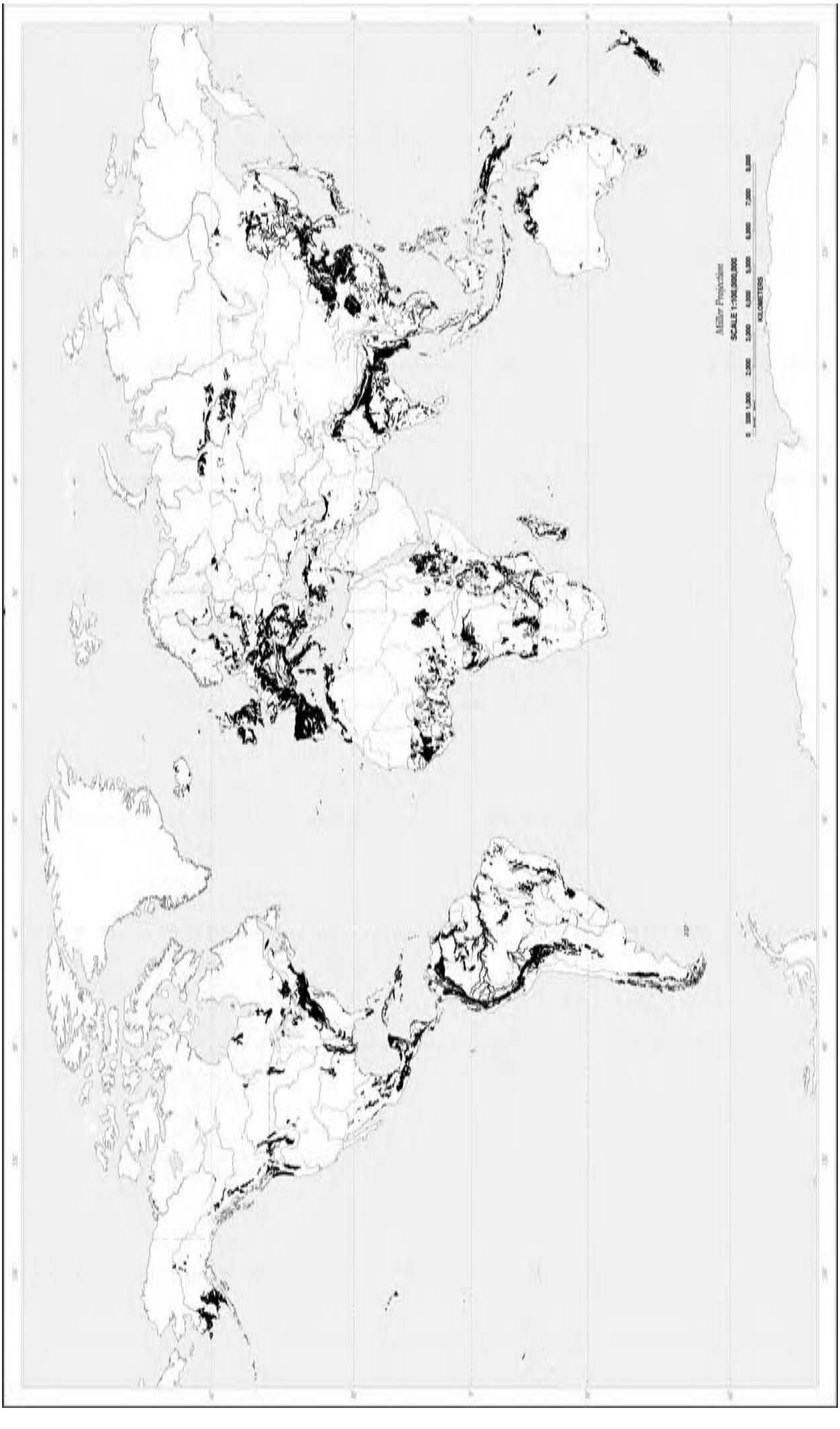


FIGURE 6.7 Global distribution of Inceptisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

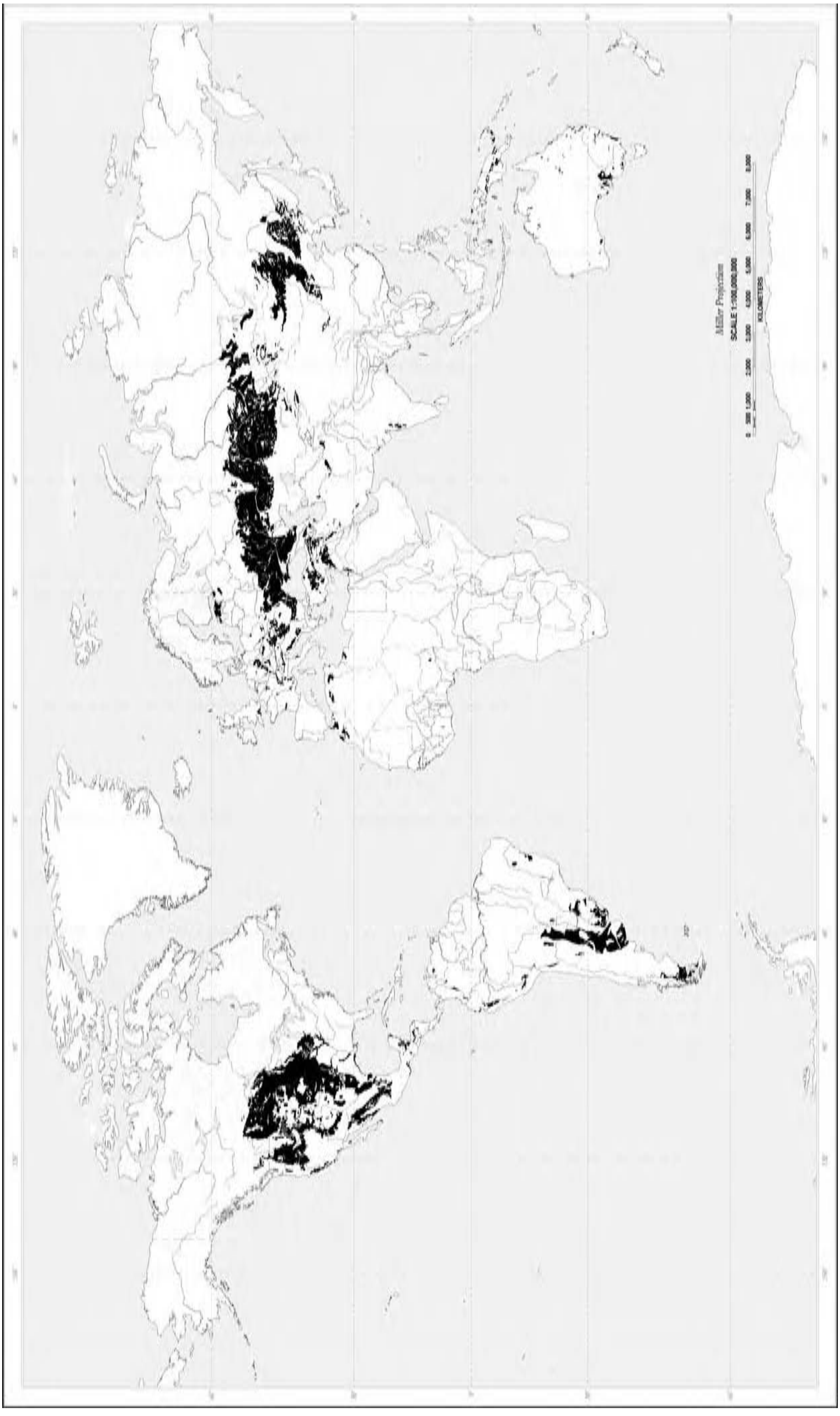


FIGURE 6.8 Global distribution of Mollisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

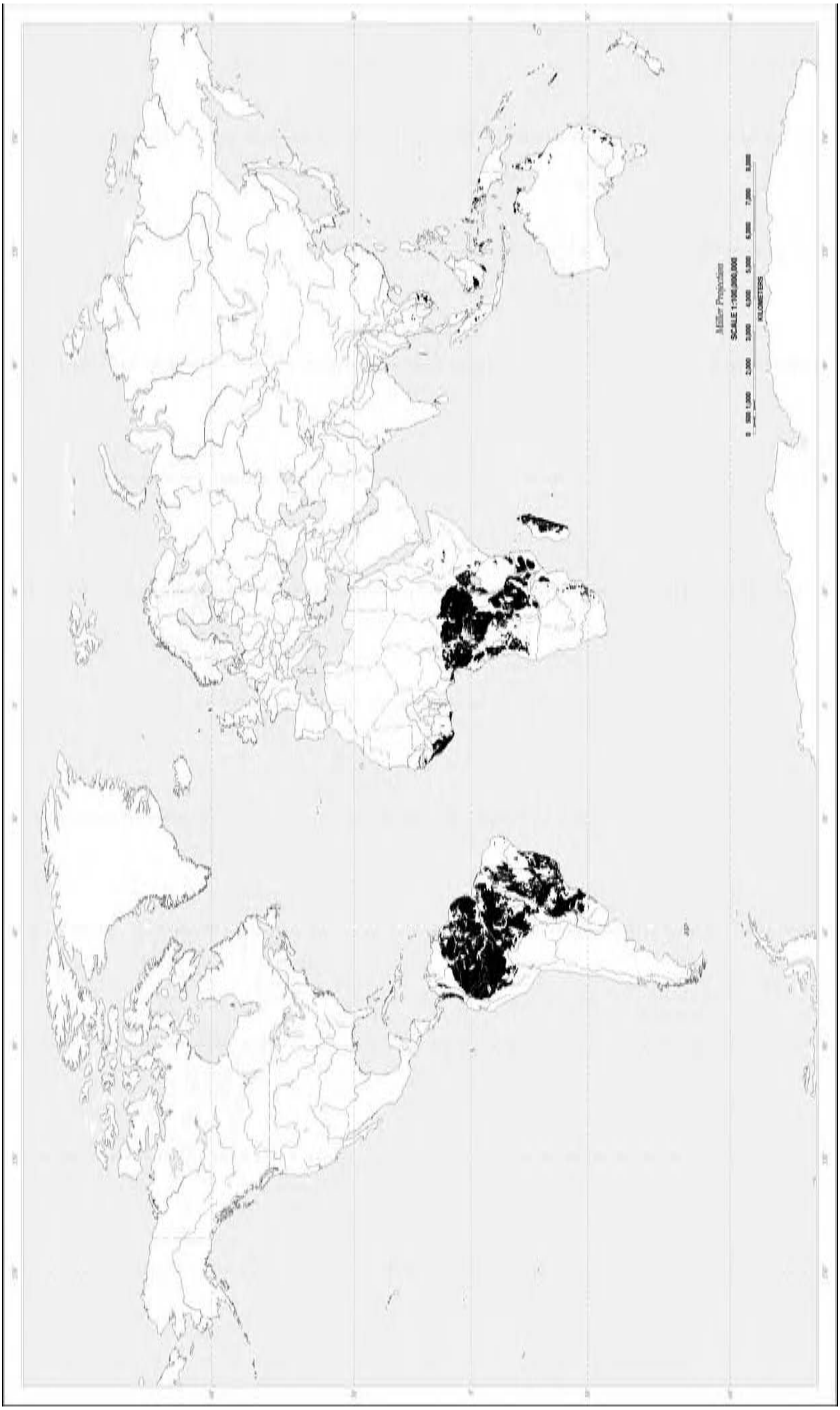


FIGURE 6.9 Global distribution of Oxisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

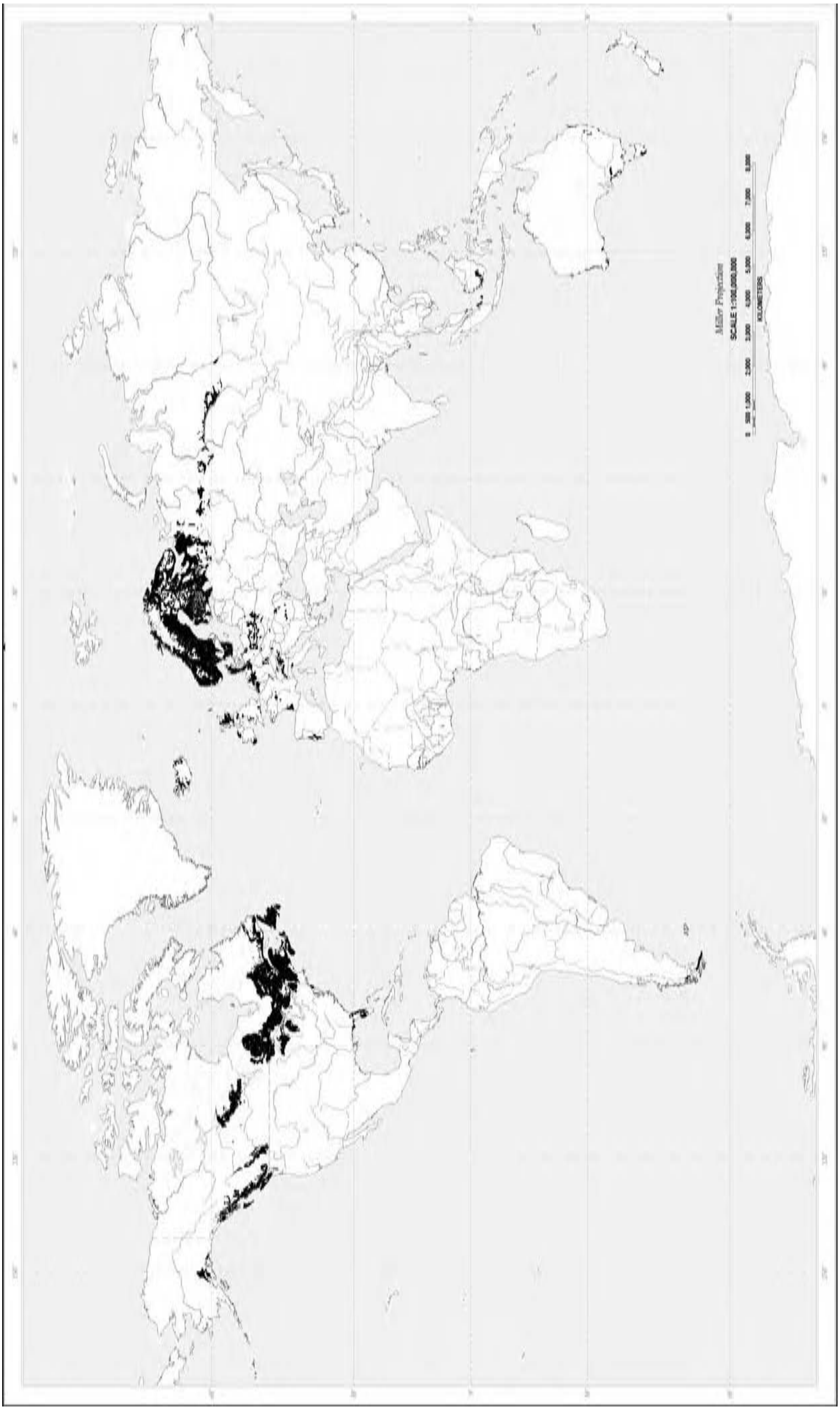


FIGURE 6.10 Global distribution of Spodosols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

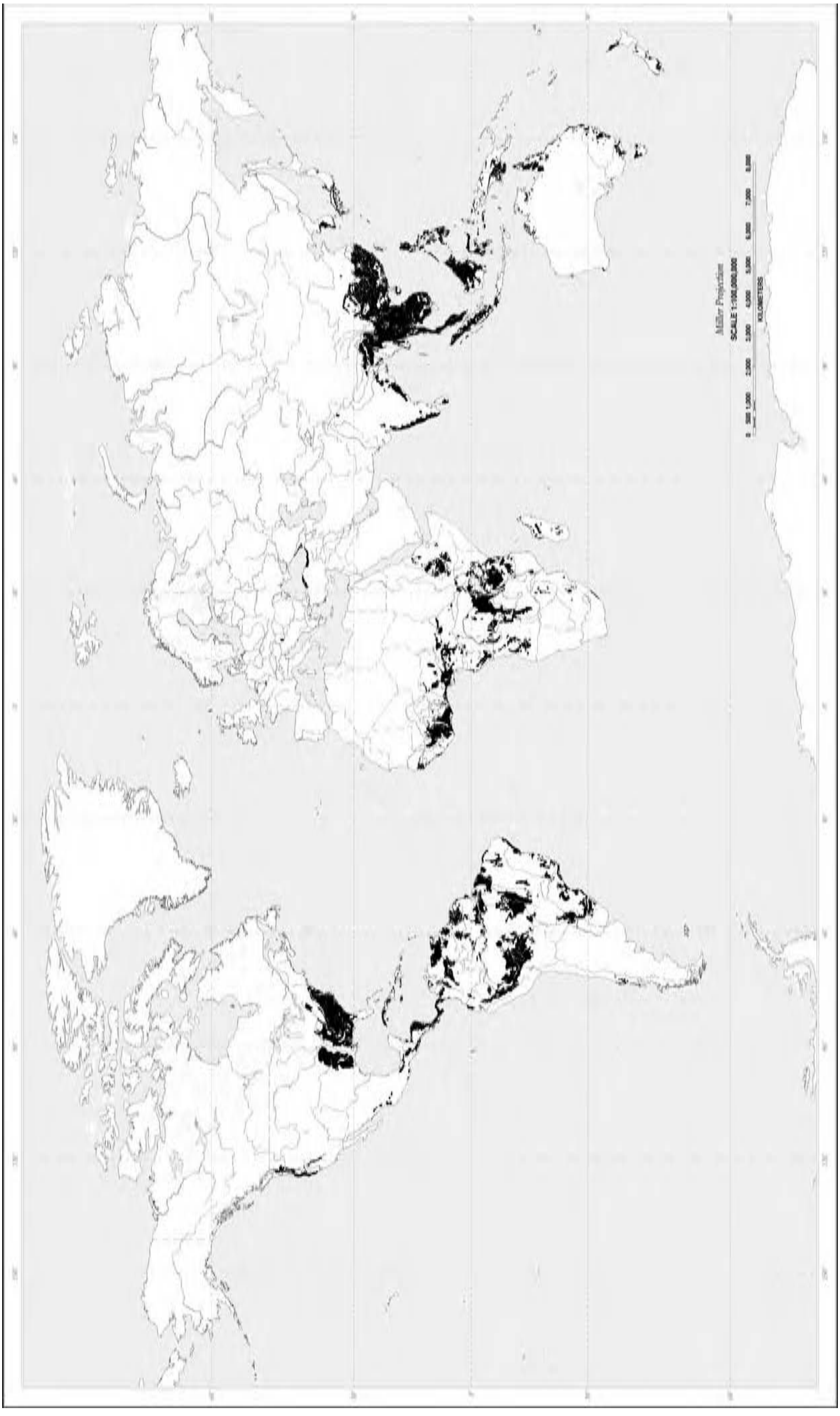


FIGURE 6.11 Global distribution of Ultisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

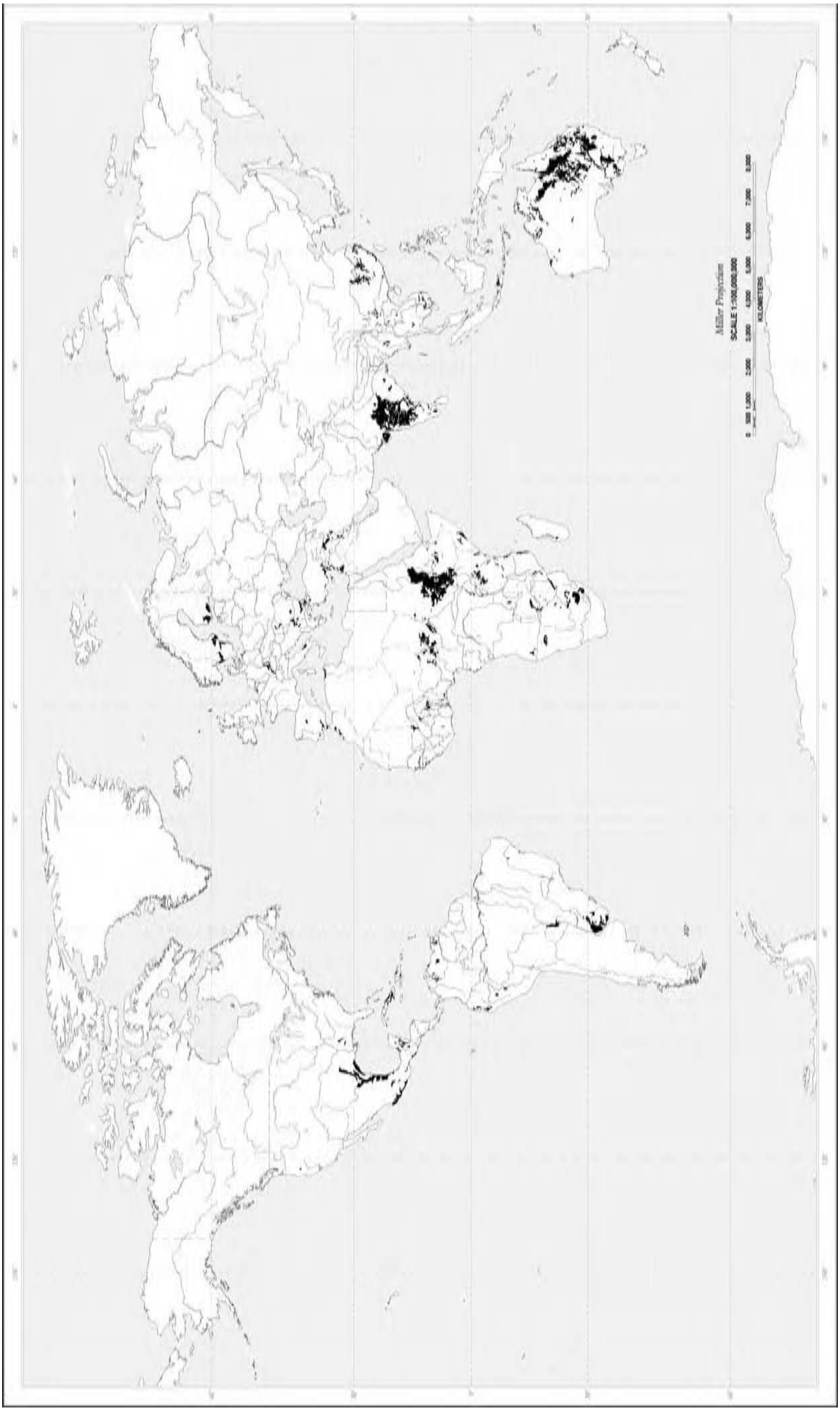


FIGURE 6.12 Global distribution of Vertisols. (*Source:* USDA-NRCS, Soil Survey Division, Washington, D.C., 1998.)

6.5 STATE SOILS

A state soil is represented by a soil series that has special significance to a particular state. Every state in the U.S. has selected a state soil and 15 of them have been established legislatively. The official state soils share the same distinctions as official state flowers and birds. Also, representative soils have been selected for Guam, Puerto Rico, and the Virgin Islands.

Areas with similar soils are grouped and labeled as soil series because their similar origins and chemical and physical properties cause them to behave similarly for land use purposes. A soil series name generally is derived from a town or landmark in or near the area where the series was first recognized. A soil series is a naturally occurring entity so a given series does not necessarily appear only within the confines of one state. For instance, 7 of the 12 state soils featured in USDA's annual *State Soil Planning Guide* extend beyond the respective states in which they are honored.

Each series consists of soils having major horizons that are similar in color, texture, structure, reaction, mineral and chemical composition, and arrangement in the soil profile. A soil profile is the sequence of natural layers or horizons in a soil. It extends from the surface downward to unconsolidated material. Most soils have three major horizons, called the surface horizon, the subsoil, and the substratum. The surface layer has the maximum accumulation of organic matter and is the horizon of maximum leaching of clay minerals and iron and aluminum oxides. Some soils have subsurface layers below their surface layers.

The subsoil underlying the surface layer or subsurface layer is the horizon of maximum accumulation of clay minerals, iron and aluminum oxides, and other compounds. These compounds may have been leached from the surface layer and redeposited in the subsoil or may have formed in place. Most likely, they result from a combination of both processes. The subsoil commonly has blocky or prismatic structure and generally is firmer and lighter colored than the surface layer. The substratum is below the surface layer and subsoil. It consists of material that was somewhat modified by weathering but is relatively unchanged by soil-forming processes.

TABLE 6.8
U.S. State Soils

State	State Soil	Legislation	Classification
Alabama	Bama	April 1997	Fine-loamy, siliceous, subactive, thermic Typic Paleudults
Alaska	Tanana		Coarse-loamy, mixed, superactive, subgelic, Typic Aquiturbels
Arizona	Casa Grande		fine-loamy, mixed, superactive, hyperthermic Typic Natrargids
Arkansas	Stuttgart	March 1997	Fine, smectitic, thermic Albaquultic Hapludalfs
California	San Joaquin	July 1997	Fine, mixed, active, thermic Abruptic Durixeralfs
Colorado	Seitz		Clayey-skeletal, smectitic Ustic Glossocryalfs
Connecticut	Windsor		Mixed, mesic Typic Udipsamments
Delaware	Greenwich		Coarse-loamy, mixed, semiactive, mesic Typic Hapludults
Florida	Myakka	May 1989	Sandy, siliceous, hyperthermic Aeric Alaquods
Georgia	Tifton		Fine-loamy, kaolinitic, thermic Plinthic Kandiudults
Guam	Akina		Fine, kaolinitic, isohyperthermic Oxic Haplustults
Hawaii	Hilo		Medial overhydrous, ferrihydritic, isohyperthermic Acrudoxic Hapludands
Idaho	Rexburg		Coarse-silty mixed, superactive, frigid Calcic Haploxerolls
Illinois	Drummer		Fine-silty, mixed, superactive, mesic Typic Endoaquolls
Indiana	Miami		Fine-loamy, mixed, active, mesic Oxyaquic Hapludalfs
Iowa	Tama		Fine-silty, mixed, superactive, mesic Typic Argiudolls

continued

TABLE 6.8 (CONTINUED)
U.S. State Soils

State	State Soil	Legislation	Classification
Kansas	Harney	April 1990	Fine, smectitic, mesic Typic Argiustolls
Kentucky	Crider	April 1990	Fine-silty, mixed, active, mesic Typic Paleudalfs
Louisiana	Ruston		Fine-loamy, siliceous, semiactive, thermic Typic Paleudults
Maine	Chesuncook	April 1999	Coarse-loamy, mixed, isotic, frigid Aquic Haplorthods
Maryland	Sassafras		Fine-loamy, siliceous, semiactive, mesic Typic Hapludults
Massachusetts	Paxton	May 1991	Coarse-loamy, mixed, active, mesic
Michigan	Kalkaska		December 1990 Sandy, mixed, frigid Typic Haplorthods
Minnesota	Lester		Fine-loamy, mixed, superactive, mesic Mollic Hapludalfs
Mississippi	Natchez		Coarse-silty, mixed, superactive, thermic Typic Eutrudepts
Missouri	Menfro		Fine-silty, mixed, superactive, mesic Typic Hapludalfs
Montana	Scobey		Fine, smectitic, frigid Aridic Argiustolls
Nebraska	Holdrege	June 1979	Fine-silty, mixed, superactive, mesic Typic Argiustolls
Nevada	Orovada		Coarse-loamy, mixed, superactive, mesic Durinodic Xeric Haplocambids
New Hampshire	Marlow		Coarse-loamy, isotic, frigid Oxyaquic Haplorthods
New Jersey	Downer		Coarse-loamy, siliceous, semiactive, mesic Typic Hapludults
New Mexico	Penistaja		Fine-loamy, mixed, superactive, mesic Ustic Haplargids
New York	Honeoye		Fine-loamy, mixed, mesic Glossoboric Hapludalfs
North Carolina	Cecil		Fine, kaolinitic, thermic Typic Kanhapludults
North Dakota	Williams		Fine-loamy, mixed, superactive, frigid Typic Argiustolls
Ohio	Miamian		Fine, mixed, active, mesic Oxyaquic Hapludalfs
Oklahoma	Port	April 1987	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls
Oregon	Jory		Fine, mixed, active, mesic Xeric Palehumults
Pennsylvania	Hazleton		Loamy-skeletal, siliceous, subactive, mesic Typic Dystrochrepts
Puerto Rico	Bayamon		Very fine, kaolinitic, isohyperthermic Typic Hapludox
Rhode Island	Narragansett		Coarse-loamy over sandy or sandy-skeletal, mixed, active, mesic Typic Dystrudepts
South Carolina	Bohicket		Fine, mixed, superactive, nonacid, thermic Typic Sulfaquents
South Dakota	Houdek		February 1990 Fine-loamy, mixed, superactive, mesic Typic Argiustolls
Tennessee	Dickson		Fine-silty, siliceous, semiactive, thermic Gossic Fragiudults
Texas	Houston Black		Fine, smectitic, thermic Udic Haplusterts
U.S.Virgin Islands	Victory		Loamy-skeletal, mixed, superactive, isohyperthermic Typic Haplusterts
Utah	Taylorsflat		Fine-loamy, mixed, superactive, mesic Xeric Haplocalcids
Vermont	Tunbridge	March 1985	Coarse-loamy, isotic, frigid Typic Haplorthods
Virginia	Pamunkey		Fine-loamy, mixed, semiactive, thermic Ultic Hapludalfs
Washington	Tokul		Medial, amorphic, mesic Aquic Vitrixerands
West Virginia	Monongahela	April 1997	Fine-loamy, mixed, semiactive, mesic Typic Fragiudults
Wisconsin	Antigo	September 1983	Coarse-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Haplic Glossudalfs
Wyoming	Forkwood		Fine-loamy, mixed, active, mesic Ustic Haplargids

Source: USDA-NRCS, *2000 State Soil Planning Guide*, U.S. Government Printing Office, Washington, D.C.

6.5 DESIGNATIONS FOR SOIL HORIZONS AND LAYERS

TABLE 6.9
Designations for Soil Horizons and Layers

Master Horizons and Layers

O horizons — Layers dominated by organic material, except limnic layers that are organic

A horizons — Mineral horizons formed at the surface or below an O horizon and (1) are characterized by an accumulation of humified organic matter intimately mixed with the mineral fraction and not dominated by properties characteristic of E or B horizons; or (2) have properties resulting from cultivation, pasturing, or similar disturbances

E horizons — Mineral horizons in which the main feature is loss of silicate clay, iron, aluminum, or some combination of these, leaving a concentration of sand and silt particles of quartz or other resistant materials

B horizons — Horizons formed below an A, E, or O horizon and are dominated by (1) carbonates, gypsum, or silica, alone or in combination; (2) evidence of removal of carbonates; (3) concentrations of sesquioxides; (4) alterations that form silicate clay; (5) formation of granular, blocky, or prismatic structure; or (6) a combination of these factors

C horizons — Horizons or layers, excluding hard bedrock, that are little affected by pedogenic processes and lack properties of O, A, E, or B horizons. Most are mineral layers, but limnic layers, whether organic or inorganic, are included

R layers — Hard bedrock including granite, basalt, quartzite, and indurated limestone or sandstone that is sufficiently coherent to make hand digging impractical

Transitional Horizons

Two kinds of transitional horizons occur. With one, the properties of an overlying or underlying horizon are superimposed on properties of the other throughout the transition zone (AB, BC, etc.). With the other, the distinct parts characteristic of one master horizon are recognizable and enclose parts characteristic of a second recognizable master horizon (E/B, B/E, and R/C).

AB — A horizon with characteristics of both an overlying A horizon and an underlying B horizon, but which is more like the A than the B

EB — A horizon with charactcristics of both an overlying E horizon and an underlying B horizon, but which is more like the E than the B

BE — A horizon with characteristics of both an overlying E horizon and an underlying B horizon, but which is more like the B than the E

BC — A horizon with characteristics of both an overlying B horizon and an underlying C horizon, but which is more like the B than the C

CB — A horizon with characteristics of both an overlying B horizon and an underlying C horizon, but which is more like the C than the B

E/B — A horizon comprised of individual parts of E and B horizon components in which the E component is dominant and surrounds the B materials

B/E — A horizon comprised of individual parts of E and B horizons in which the E component surrounds the B component but the latter is dominant

B/C — A horizon comprised of individual parts of B and C horizons in which the B horizon component is dominant and surrounds the C component

Subordinate Distinctions within Master Horizons and Layers

a — Highly decomposed organic material where rubbed fiber content averages <1/6 of the volume

b — Identifiable buried genetic horizons in a mineral soil

c — Concretions or hard nonconcretionary nodules of iron, aluminum, manganese, or titanium cement

e — Organic material of intermediate decomposition in which rubbed fiber content is 1/6 to 2/5 of the volume

f — Frozen soil in which the horizon or layer contains permanent ice

g — Strong gleying in which iron has been reduced and removed during soil formation or in which iron has been preserved in a reduced state because of saturation with stagnant water

h — illuvial accumulation of organic matter in the form of amorphous, dispersible organic matter; sesquioxide complexes where sesquioxides are in very small quantities and the value and chroma of the horizon are <3

continued

TABLE 6.9 (CONTINUED)
Designations for Soil Horizons and Layers

i — Slightly decomposed organic material in which rubbed fiber content is more than about 2/5 of the volume
k — Accumulation of pedogenic carbonates, commonly calcium carbonate
m — Continuous or nearly continuous cementation or induration of the soil matrix by carbonates (km), silica (qm), iron (sm), gypsum (ym), carbonates and silica (kqm), or salts more soluble than gypsum (zm)
n — Accumulation of sodium on the exchange complex sufficient to yield a morphological appearance of a natric horizon.
o — Residual accumulation of sesquioxides
p — Plowing or other disturbance of the surface layer by cultivation, pasturing or similar uses
q — Accumulation of secondary silica
r — Weathered or soft bedrock including saprolite; partly consolidated soft sandstone, siltstone or shale; or dense till that roots penetrate only along joint planes and are sufficiently incoherent to permit hand digging with a spade
s — Illuvial accumulation of sesquioxides and organic matter in the form of illuvial, amorphous, dispersible organic matter; sesquioxide complexes if *both* organic matter and sesquioxide components are significant and the value and chroma of the horizon are >3
t — Accumulation of silicate clay that either has formed in the horizon and is subsequently translocated or has been moved into it by illuviation
v — Plinthite which is composed of iron-rich, humus-poor, reddish material that is firm or very firm when moist and that hardens irreversibly when exposed to the atmosphere under repeated wetting and drying
w — Development of color or structure in a horizon but with little or no apparent illuvial accumulation of materials
x — Fragic or fragipan characteristics that result in genetically developed firmness, britor high bulk density
y — Accumulation of gypsum
z — Accumulation of salts more soluble than gypsum

REFERENCES

1. *Glossary of Soil Science Terms*, 1987, Soil Science Society of America, Madison, WI.

Part III

Soils and Their Properties

7 Physical, Chemical, and Biological Properties of Soils

7.1 CATION EXCHANGE CAPACITIES OF SOILS AND SOIL COMPONENTS

TABLE 7.1
Representative Cation Exchange Capacities (CECs) of Surface Soils by Soil Order

Soil Order	CEC (molc/kg)	Soil Order	CEC (molc/kg)
Alfisols	0.12	Mollisols	0.22
Aridisols	0.16	Oxisols	0.05
Entisols	0.43	Spodosols	0.11
Histisols	1.40	Ultisols	0.06
Inceptisols	0.19	Vertisols	0.37

Source: Sumner, M.E., Ed., *Handbook of Soil Science*, 2000, CRC Press, Boca Raton, FL, p B-241.

TABLE 7.2
Specific Surfaces of Clay Minerals and Soils

Component	Specific Surface (m^2/g)
Kaolinite	15–20
Illite	80–100
Bentonite	115–260
Montimorillonite	280–500
Organic matter	560–800
Calcite	0.047
Crystalline iron oxides	116–184
Amorphous iron oxides	305–410
Sands	<10
Sandy loams and silt loams	5–20
Clay loams	15–40
Clay soils	>25

TABLE 7.3
Charge Characteristics and Cation Exchange Capacities (CECs) of Clay Minerals

Clay Mineral	Charge per Unit Half Cell		CEC (cmol/kg)
	Tetrahedral	Octahedral	
Kaolinite	0	0	1–10
Smectite			80–120
Montmorillonite	0	–0.33	
Beidellite	–0.5	0	
Vermiculite	–0.85	+0.23	120–150
Mica			20–40
Muscovite	–0.89	–0.05	
Chlorite			10–40

TABLE 7.4
Cation Exchange Capacities (CECs) of Clay Minerals

Clay	CEC (meq/100 g)
Kaolinite	5–15
Chlorite	10–40
Illite	20–50
Transitional minerals	40–0
Montmorrillonite (smectite)	80–120
Vermiculite	100–150
Humic material	200–500

TABLE 7.5
Cation Exchange Capacities (CECs) of Soil Colloids

Type of Colloid	Cation Exchange Capacity	
	Mean (meq/100 g)	Range (meq/100 g)
Humus	200	100–300
Vermiculite	150	100–200
Allophane	100	50–200
Montmorillonite	80	60–100
Illite	30	20–40
Chlorite	30	20–40
Peat	20	10–30
Kaolinite	8	3–15

TABLE 7.6
Approximate Cation Exchange Capacities (CECs) Related to Textural Classes of Soils with Water pH Levels below 7.0

Soil Textural Class	CEC (meq/100 g soil)
Sand	1–8
Loamy sand	9–12
Sandy or silty loam	13–20
Loam	21–28
Clay loam	29–40
Clay	>40

TABLE 7.7
Classification Scheme for Phyllosilicates Related to Clay Minerals

Type	Group (x ~ charge per formula unit)	Subgroup	Species[a]
1:1	Kaolin-serpentine	Kaolins	Kaolinite, halloysite (7 Å or 0.7 nm), halloysite (10 Å or 1.0 nm)
	x ~ 0	Serpentines	Chrysotile, lizardite, antigorite
2:1	Pyrophyllite-talc	Pyrophyllites	Pyrophyllite
	x ~ 0	Talcs	Talc
	Smectite	Dioctahedral smectites	Montmorillonite, beidellite, nontronite
	x ~ 0.25–0.6	Trioctahedral smectites	Saponite, hectorite, sauconite
	Vermiculite	Dioctahedral vermiculite	Dioctalledral vermiculite
	x ~ 0.6–0.9	Trioctahedral vermiculite	Trioctahedral vermiculite
	Mica	Dioctahedral micas	Muscovite paragonite
	x ~ 1	Trioetahedral micas	Biotite, phlogopite
	Brittle mica	Dioetahedral brittle micas	Margarite
	x ~ 2	Trioctahedral brittle micas	Clintonite
	Chlorite	Dioctahedral chlorites (4-5 octahedral cations/formula unit)	
	x variable	Trioctahedral chlorites 5-6 octahedral cations/formula unit	Pennine, chlinochlore, prochlorite

[a] Only a few examples are given.

7.2 TEXTURE

7.2.1 TEXTURAL CLASSES

The 12 textural classes (sand, loamy sand, sandy loam, sandy clay loam, sandy clay, loam, silt loam, silt, clay loam, silty clay loam, silty clay, clay) of soils can be determined by knowing the relative percentages of the three major soil separates (sand, silt, and clay) as illustrated in Figure 7.1.

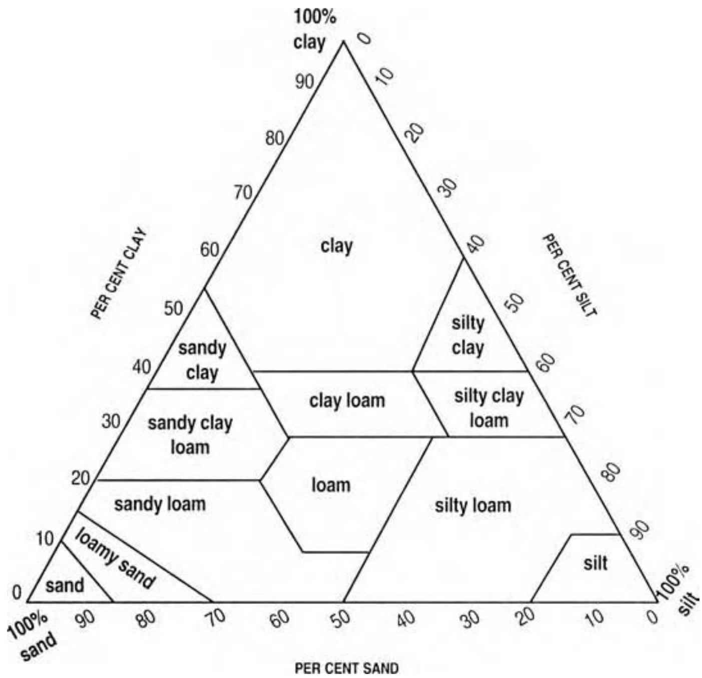


FIGURE 7.1 Soil textural classes based on percentage content of sand, silt, and clay.

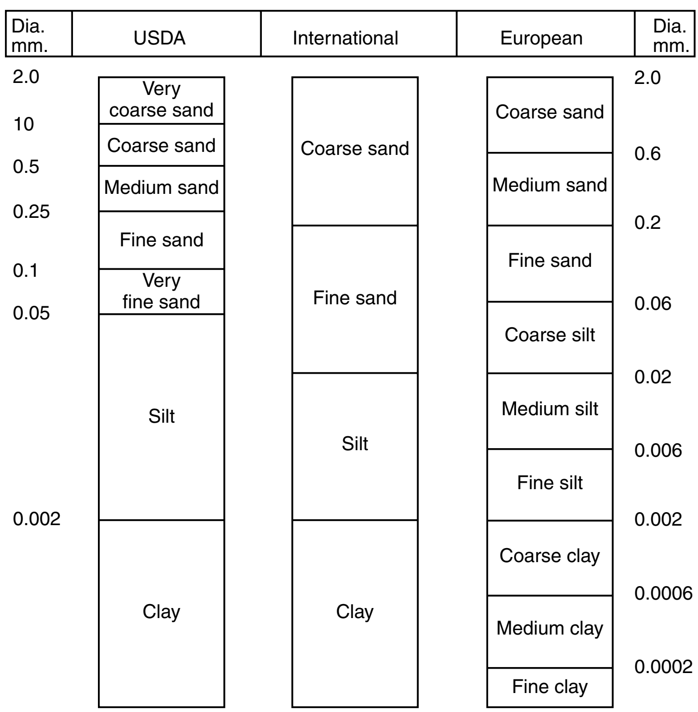


FIGURE 7.2 Comparison of particle size limits of four systems of particle size classification. (From McKeague, J.A., Ed., *Manual on Soil Sampling and Methods of Analysis*, 2nd ed., Canada Society of Soil Science, Ottawa, Ontario, 1978. With permission.)

7.2.2 Soil Separates (USDA Classification)

Soil separates are defined by particle diameter size based on the USDA classification as follows:

Separate	Diameter (mm)
Fine gravel	2.0–1.0
Coarse gravel	1.0–0.5
Medium sand	0.05–0.25
Fine sand	0.25–0.10
Very fine sand	0.01–0.05
Silt	0.05–0.002
Clay	Below 0.02

The international system for size limits of soil separates is as follows:

Fraction	Diameter range (mm)
I	2.0–0.2
II	0.20–0.02
III	0.02–0.002
IV	Below 0.002

The amounts of sand, silt, and clay in a soil can be determined by several methods, although all are based on the same basic principle — varying settling velocities due to different particle sizes in a standing column of water (the principle of sedimentation is known as Stokes' Law). This technique is frequently referred to as a mechanical analysis. Particle separation by varying settling velocity assumes a consistent particle density (2.65 g/cm^3) for all the separates.

7.2.3 Hydrometer Procedure

7.2.3.1 Soil Preparation

1. Weigh 50 g air-dried <10-mesh-sieved (2-mm) soil (100 g for sandy soils) into a beaker and add 100 mL 5% Calgon solution. Stir and let stand overnight (8 hr). Transfer the entire contents of the beaker into a dispersion cup and fill the cup 2/3 full with water. Add 1 drop of soil and place the cup on a Humboldt Mixer. Mix for 2 min. Remove the cup and cleanly transfer its entire contents into a 1,000-mL cylinder.
2. Bring to the mark (1,000 mL for 50-g sample, 1,120 mL for 100-g sample) with water.

7.2.3.2 Hydrometer Readings

1. Cap the cylinder and invert 10 times with vigor. Put the cylinder down; uncap and place the Bouyoucos hydrometer (calibrated in g/L) into the water–soil slurry.
2. After 40 sec of standing, take a hydrometer reading. Place a therometer into the slurry. Determine its temperature and record both readings.
3. Let the cylinder stand undisturbed for 2 hr, then take additional hydrometer and temperature readings.

7.2.3.3 Blank Determination

1. Dilute 100 mL 5% Calgon solution to 1000 mL with water in a 1000-mL cylinder. Take a Bouyoucos hydrometer reading and determine the temperature of the solution.

7.2.3.4 Calculations for Percentages of Sand, Silt, and Clay

Percentages of silt and clay: 40-sec hydrometer reading: (sample − blank) + temperature correction (see note below)/weight of soil sample in g.

Percentage of sand: 100 − percent silt + percent clay.

Percentage of clay: 2-hr hydrometer reading: (sample − blank) + temperature correction (see note below)/weight of soil sample in g.

Percentage of silt: 100 − percent sand − percent clay.

Note regarding temperature correction: Degrees below 19.4°C (67°F): subtract 0.2 units/degree from hydrometer reading. Degrees above 19.4°C (67°F): add 0.2 units/degree to hydrometer reading.

7.3 SOIL SEPARATE DEFINITIONS[1]

7.3.1 Sands

Very coarse sand Contains 85% or more sand; percentage of silt plus 1.5 times the percentage of clay shall not exceed 15.

Coarse sand Contains 25% or more very coarse and coarse sand and <50% any other single grade of sand.

Medium sand Contains 25% or more very coarse, coarse, and medium sand, and <50% fine or very fine sand.

Fine sand Contains 50% or more fine sand or <25% very coarse, medium sand, and <50% very fine sand.

Very fine sand Contains 50% or more fine sand.

Loamy sand Soil material that contains at the upper limit 85 to 90% sand; the percentage of silt plus 1.5 times the percentage of clay is not less than 15; at the lower limit, contains not less than 70 to 85% sand and the percentage of silt plus twice the percentage of clay exceeds 30.

Loamy coarse sand Contains 25% or more very coarse and coarse sand and <50% any other single grade of sand.

Loamy sand Contains 25% or more very coarse, coarse, and medium sand and <50% fine or very fine sand.

Loamy fine sand Contains 50% or more very fine sand or <25% very coarse, coarse, and medium sand and <50% very fine sand.

Loamy very fine sand Contains 50% or more very fine sand.

7.3.2 Loams

Sandy loam Soil material that contains either 20% clay or less and the percentage of silt plus twice the percentage of clay exceeds 30 and 52% or more sand; or <7% clay, <50% silt, and 43 to 52% sand.

Coarse sandy loam Loam that contains 25% or more very coarse and coarse sand and <50% any other one grade of sand.

Sandy loam Contains 30% or more very coarse, coarse, and medium sand, <25% very coarse sand, and <30% very fine or fine sand, or <15% very coarse or coarse and <30% fine sand or very fine sand.

Fine sandy loam Contains 30% or more fine sand and <30% very fine sand or 15 to 30% very coarse, coarse, and medium sand, or >40% fine and very fine sand, at least half of which is fine sand, and <15% very coarse, coarse, and medium sand.
Very fine sandy loam Contains 30% or more very fine or >40% fine and very fine sand, more than half of which is very fine sand, and <15% very coarse, coarse, and medium sand.
Loam Soil material that contains 7 to 27% clay, 28 to 50% silt, and <52% sand.
Silt loam Soil material that contains 50% or more silt and 12 to 27% clay or 50 to 80% silt and <2% clay.
Silt Soil material that contains 80% or more silt and <12% clay.
Sandy clay loam Soil material that contains 20 to 35% clay, <28% silt, and 45% or more sand.
Clay loam Soil material that contains 27 to 40% clay and 20 to 45% sand.
Silty clay loam Soil material that contains 27 to 40% clay and <20% sand.

7.3.3 Clays

Sandy clay Soil material that contains 35% or more clay and 45% or more sand.
Silty clay Soil material that contains 40% or more clay and 40% or more silt.
Clay Soil material that contains 40% or more clay, <45% sand, and <40% silt.

TABLE 7.8
Particle Size Fraction Comparison

Size Fraction (μm)	Approximate No. Particles/g	Approximate Specific Surface ($cm^{2/g}$)
2,000–200	$5 \cdot 10^2$	20
200–20	$5 \cdot 10^5$	200
20–2	$5 \cdot 10^8$	2,000
2–0.2	$5 \cdot 10^{11}$	20,000 - $2m^3$ = 2000,000

TABLE 7.9
Particle Size Fraction Designations

Equivalent Diameter (mm)	Description
>600	Rocks
660–200	Stones
200–75	Cobbles
75–2	Gravel
2.0–0.6	Coarse sand
0.6–0.2	Medium sand
0.2–0.06	Fine sand
0.06–0.02	Coarse silt
0.02–0.006	Medium silt
0.006–0.002	Coarse silt
0.002–0.0006	Coarse clay
0.0006–0.0002	Medium clay
<0.0002	Fine clay

TABLE 7.10
Approximate Bulk Densities that Restrict Root Penetration by Soil Texture

	Critical Bulk Density for Soil Resistance	
Texture	High (mg/m^3)	Low (mg/m^3)
Sandy	1.85	1.60
Coarse loamy	1.80	1.40
Fine loamy	1.70	1.40
Coarse, fine silty	1.60	1.30
Clayey	Depends on clay percent and structure	

Source: Sumner, M.E., Ed., *Handbook of Soil Science*, 2000, CRC Press, Boca Raton, FL. With permission.

TABLE 7.11
Bulk Density versus Percent Volume of Solids and Pores[a]

Bulk Density	kg/m^3	% solids	% pores
1.0	1,000	38	62
1.1	1,100	42	58
1.2	1,200	45	55
1.3	1,300	49	51
1.4	1,400	53	47
1.5	1,500	57	43
1.6	1,600	60	40

[a] 2.65 g/cm^3 particle density.

7.4 PHYSICAL CHARACTERISTICS

TABLE 7.12
Composition of Grassland Soil

Volume Percent	Component
45	Mineral components: fragments of parent rock, primary and secondary minerals, amorphous substance
7	Organic components: soil fauna and flora, plant roots, intact decaying plant residues, newly formed humic substances (humus)
25	Air
23	Water

7.4.1 Consistence

Consistence is the sum effect of particle size distribution, organic matter content, soil structure, and stability at the prevailing water content level. The main factors that determine consistence are clay and water contents.

TABLE 7.13
Consistence Levels

Loose	Easy to work; neither sticky nor malleable
Sticky	Adheres to hands and implements
Plastic	Smooth and malleable; subject to smearing when cultivated
Friable	Breaks into crumbs under gentle pressure; not sticky; does not smear
Firm	Not friable even under high stress; cloddy when cultivated

7.4.2 Water Holding and Infiltration Rates

Plants consume, on the average, 0.1 to 0.3 inches of rainfall or irrigation per day. They use more in hot, dry weather than in cool weather. Well fertilized crops require less water than poorly fertilized crops.

TABLE 7.14
Approximate Amounts of Water Held by Different Soils

Soil Texture	Inches of Water Held/Ft of Soil	Maximum Rate of Irrigation In./Hr Bare Soil
Sand	0.5–0.7	0.75
Fine sand	0.7–0.9	0.60
Loamy sand	0.7–1.1	0.50
Loamy fine sand	0.8–1.2	0.45
Sandy loam	0.8–1.4	0.40
Loam	1.0–1.8	0.35
Silt loam	1.2–1.8	0.30
Clay loam	1.3–2.1	0.25
Silty clay	1.4–2.5	0.20
Clay	1.4–2.4	0.15

Source: *Western Fertilizer Handbook, Horticulture Edition*, 1990, Interstate Publishers, Danville, IL. With permission from California Plant Health Association.

TABLE 7.15
Soil Moisture Constants and Corresponding Tension Values

Soil Moisture Constant	cm H_2O	Bars	pF	MPa
Maximum retentive capacity	0	0	0	0
Field capacity	346	0.3	2.54	0.03
Moisture equivalent	1,000	1	3.0	0.1
Wilting point	15,849	15	4.2	1.5
Hygroscopic coefficient	31,623	31	4.5	3.1
Air dry soil	1×10^6	1,000	6.0	100
Oven dry soil	1×10^7	10,000	7.0	1,000

TABLE 7.16
Approximate Water Storage Capacity of Soils

Soil Texture	Total Storage (in./ft)	Available Water (in./ft)
Coarse sand	1.0–1.5	0.6–0.8
Sandy loams (coarse to medium)	2.0–2.5	1.0–1.5
Silts and loams (medium)	3.5–4.0	1.6–2.0
Clay loams (medium to fine)	4.0–4.5	2.0–2.5
Clays (fine)	4.5–5.0	1.6–2.0

TABLE 7.17
Infiltration Rates

Soil Texture	Good Physical Condition (in./hr)	Poor Physical Condition (in./hr)
Coarse sand	2.0–3.0	1.2–1.6
Fine sand	1.8–2.0	0.8–1.2
Sandy loams	1.2–1.8	0.5–1.0
Silts and loams	1.0–1.2	0.3–0.4
Clay loams	0.5–1.0	0–0.3
Clays	0.2–0.5	0.0.2

TABLE 7.18
Options for Improving Irrigation Water Productivity

Technical Options
Land leveling to apply water more uniformly
Surge irrigation to improve water distribution
Efficient sprinklers to apply water more uniformly
Low energy precision application sprinklers that cut evaporation and wind drift losses
Furrow diking to promote soil infltration and reduce runoff
Drip irrigation to cut evaporation and other water losses and increase crop yields
Managerial Options
Better irrigation scheduling
Improving canal operations for timely deliveries
Applying water when most crucial to crop yield
Water-conserving tillage and field preparation methods
Better maintenance of canals and equipment
Recycling drainage and tail water
Institutional Options
Establishing water user organizations for better involvement of farmers and collection of fees
Reducing irrigation subsidies and/or introducing conservation-oriented pricing
Establishing legal framework for implementing efficient and equitable water markets
Fostering rural infrastructure for private sector dissemination of efficient technologies
Better training and extension efforts
Agronomic Options
Selecting crop varieties with high yields/liter of transpired water
Intercropping to maximize use of soil moisture
Better matching crops to climate conditions and quality of available water
Sequencing crops to maximize output under soil and water salinity conditions
Selecting drought-tolerant crops where water is scarce or unreliable
Breeding water-efficient crop varieties

Source: Sumner, M.E., Ed., *Handbook of Soil Science,* 2000, CRC Press, Boca Raton, FL. With permission.

7.5 NUTRIENT ELEMENT CONTENTS OF SURFACE SOILS

TABLE 7.19
Amounts of Plant Nutrient Elements Ordinarily Present in 15 cm of Surface Soil in Humid Region

Nutrient Element	Range (%)	Amount (kg/ha)
Nitrogen	0.02–0.50	450–11,000
Phosphorus	0.01–0.20	200–4,500
Potassium	0.17–3.30	3,800–74,000
Calcium	0.07–3.60	1,600–81,000
Magnesium	0.12–1.50	2,700–34,000
Sulfur	0.01–0.20	200–4,500
Iron	0.50–5.00	11,000–112,000
Manganese	0.20–1.00	4,500–22,000
Zinc	0.001–0.025	22–560
Boron	0.0005–0.015	11–340
Copper	0.0005–0.015	11–340
Chlorine	0.001–0.10	22–2,240
Cobalt	0.0001–0.005	2–112
Molybdenum	0.00002–0.0005	0.5–11

TABLE 7.20
Common Concentration Levels of Micronutrients/Trace Elements (ppm) in Mineral Soils

Micronutrient/Trace Element	Normal Range	Extreme Values
Iron	15,000–40,000	10–80,000
Manganese	300–7,000	12–10,000
Chlorine	30–450	5–800
Vanadium	12–700	1–900
Zinc	10–500	4–10,000
Copper	3–100	0.1–1,300
Boron	3–100	0.1–1,300
Cobalt	1–60	0.1–600
Molybdenum	0.4–7	0.1–80
Selenium	0.1–3	0.1–70

TABLE 7.21
Nutrient Elements in Soil

Element	Ionic Form Taken Up	Most Important Sources	Usual Content
		Major Elements	
Nitrogen	NO_3-	Organic matter, N^z from atmosphere	0.03–0.3%
	NH_4^+		
Phosphorus	H_2PO_4-	Ca, Al, and Fe phosphates	0.01–0.1%
	HPO_4^{2-}		
	PO_4^{3-}		
Sulfur	SO_4^{2-}	Fe sulfide and sulfate	0.01–0.1%
Potassium	K^+	Micas, illite, K feldspar	0.2–3.0%
Calcium	Ca^{2+}	Ca feldspar, augite, hornblende, $CaCO_3$, $CaSO_4$	0.2–1.5%[a]
Magnesium	Mg^{2+}	Augite, hornblende, olivine, biotite, $MgCO_3$	0.1–1.0%[b]
		Micronutrients	
Boron	$H_2BO_3^-$	Tourmaline, accessory in silicates and salts	5–100 mg/kg
	HBO_3^{2-}		
	$B(OH)_4^-$		
Chlorine	Cl^-	Various chlorides	50–1,000 mg/kg
Copper	Cu^{2+}	Cu sulfide, sulfate, carbonate	5–100 mg/kg
	Cu^+		
Iron	Fe^{2+}	Augite, hornblende, biotite, olivine, Fe oxide, and hydroxide	0.5–4.0%[c]
	Fe^{3+}		
Manganese	Mn^{2+}	Manganite, pyrolusite, accessory in silicates	200–400 mg/kg
	Mn^{3+}		
Molybdenum	MoO_4^{2-}	Accessory in silicates, Fe- and Al oxides and hydroxides	0.5–5 mg/kg
Zinc	Zn^{2+}	Zn phosphate, carbonate, hydroxide, accessory in silicates	10–300 mg/kg

[a] Except chalk soils.
[b] Except dolomitic soils.
[c] Except Fe-enriched horizons.

7.6 ORGANIC MATTER

7.6.1 Organic Matter Determination

7.6.1.1 Titration Procedure

7.6.1.1.1 Reagents

Potassium dichromate reagent: Weigh 13.072 g 0.267*N* potassium dichromate ($K_2Cr_2O_7$) into a 1,000-mL volumetric flask.

Add 400 mL water to dissolve, then add 550 mL concentrated sulfuric acid (H_2SO_4). Let cool and bring to volume with water.

Mohr's Salt Solution (0.2M): Weigh 78.390 g ferrous ammonium sulfate [$Fe(NH_4)_2(SO_4){\cdot}6H_2O$] into a 1000-mL volumetric flask.

Add 500 mL water to dissolve, then add 50 mL concentrated H_2SO_4. Let cool and bring to volume with water. Prepare fresh for each use.

Indicator Solution: Weigh 200 mg n-phenylanthranilic acid into a 1,000-mL volumetric flask containing 0.2% sodium carbonate (Na_2CO_3) solution.

7.6.1.1.2 Determination

Weigh 0.1 to 0.5 g (depending on estimated organic content) of air-dried <10-mesh screened (2-mm) soil into a 500-mL Erlenmeyer flask and add 15 mL 0.267*N* potassium dichromate reagent.

Connect the flask to a reflux condenser and boil for 30 min; let cool.

Wash down the condenser and flush with pure water. Add 3 drops of indicator solution and titrate with Mohr's Salt Solution at room temperature.

As the end point is approached, add a few more drops of the indicator solution. The color change is from violet to bright green.

A blank analysis with no soil added is carried through the procedure.

7.6.1.1.3 Calculation

$$\text{Percent organic carbon} = \{[(\text{meq } K_2Cr_2O_7 - \text{meq } FeSO_4) \text{ x } 0.3]/\text{g soil}\} \times 1.15$$

$$\text{Percent organic matter} = \text{percent organic carbon} \times 1.724$$

7.6.1.2 Loss-on-Ignition Procedure

Weigh 5.00 to 10.00 g (to the nearest 0.01 g) sieved 2-mm soil into an ashing vessel (50-mL beaker or other suitable vessel).

Place the ashing vessel and soil into a drying oven set at 105°C (221°F) and dry for 4 hr.

Remove the ashing vessel from the drying oven and place in a dry atmosphere.

When cooled, weigh to the nearest 0.01 g.

Place the ashing vessel plus soil into a muffle furnace and bring the temperature to 400°C (752°F). Ash in the furnace for 4 hr.

Remove the ashing vessel from the muffle furnace; let cool in a dry atmosphere and weigh to the nearest 0.01 g.

7.6.1.2.1 Calculation

$$\text{Percent organic matter in soil} = [(W_{105} - W_{400}) \times 100]/W_{105}$$

where W_{105} is the weight of soil at 105°C (221°F) and W_{400} is the weight of soil at 400°C (752°F)

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TABLE 7.22
Functions of Organic Matter and Organisms in Soil

Components of organic matter can:

Attract and hold cation nutrient elements and trace elements in an available state, reducing leaching losses.
Bind soil particles into aggregates, producing a granular structure that allows root accessibility to air, capillary movement of water, and penetration of roots through soil.
Soak up water.
Be transformed into vitamins, hormones, and other substances that stimulate growth of plants and soil organisms.
Be transformed into plant toxins that suppress weeds.

Soil organisms can:

Fix nitrogen (N_2) from the air.
Form symbiotic relationships with plant roots, thereby serving the plants as extensions in their searches for mineral nutrient elements.
Produce vitamins, growth hormones, and organic acids (effective solvents of minerals) as by-products of metabolism.
Contribute to soil aggregation and distribution of nutrient elements by binding organic matter and mineral particles or by feeding on plant debris, mixing it throughout the soil, and forming tunnels and nutrient-rich fecal matter.
Prey on plant pathogens.
Produce carbon dioxide (CO_2) as a metabolism by-product that passes through the soil and into the atmosphere and becomes a source for absorption of carbon by plant leaves.

Source: Parnes, R., *Fertile Soil: A Grower's Guide to Organic and Inorganic Fertilizers*, 1990, AgAccess, Davis, CA. With permission.

TABLE 7.23
Properties and Functions of Organic Matter in Soil

Property	Function
	Biological Properties
Reservoir of metabolic energy	Organic matter provides the metabolic energy that drives soil biological processes.
Source of macronutrients	The mineralization of soil organic matter can positively or negatively influence the size of the available macronutrient (N, P, and S) pools.
Ecosystem resilience	The build-up of significant pools of organic matter and associated nutrients can enhance the ability of an ecosystem to recover after imposed natural or anthropogenic perturbations.
Stimulation and inhibition of enzyme activities and plant and microbial growth	The activity of enzymes found in soils and the growth of plants and microorganisms can be stimulated or inhibited by the presence of soil humic materials.
	Physical Properties
Stabilization of soil structure	Through the formation of bonds with the reactive surfaces of soil mineral particles, organic matter is capable of binding individual particles and aggregations of soil particles into water-stable aggregates at scales ranging from <2 μm for organic molecules to millimeters for plant roots and fungal hyphae.
Water retention	Organic matter can affect water retention directly through its ability to absorb up to 20 times its mass of water and indirectly through its impact on soil structure and pore geometry.
Low solubility	Ensures that the bulk of organic materials added to the soil are retained and not leached out of the soil profile.
Color	The dark color soil organic matter imparts may alter thermal properties.
	Chemical Properties
Cation exchange capacity	The high charge characteristics of soil organic matter enhance retention of cations (e.g., Al^{3+}, Fe^{3+}, Ca^{2+}, Mg^{2+}, NH_4^+,) and transition metal micronutrients.
Buffering capacity and pH effects	In slightly acidic to alkaline soils, organic matter can act as a buffer and aids in the maintenance of acceptable soil pH conditions.
Chelation of metals	Stable complexes formed with metals and trace elements enhance the dissolution of soil minerals, reduce losses of soil micronutrients, reduce the potential toxicity of metals, and enhance the availability of P.
Interactions with xenobiotics	Organic matter can alter the biodegradability, activity, and persistence of pesticides in soils.

Source: Sumner, M.E., Ed., *Handbook of Soil Science*, 2000, CRC Press, Boca Raton, FL, p. B-29.

7.7 SOIL COMPONENT GLOSSARY

Soil organic matter (SOM) All natural and thermally altered, biologically derived organic material found in the soil or on the soil surface regardless of source or stage of decomposition, whether living or dead, and excluding the above-ground portions of living plants.

Phytomass Living tissue of plant origin; standing plant components that are dead (e.g., standing dead trees) are also considered phytomass.

Microbial biomass Organic matter associated with cells of living soil microorganisms.

Faunal blomass Organic matter associated with living soil fauna.

Nonliving component Organic fragment with a recognizable cellular structure derived from any source but usually dominated by plant-derived materials.

Litter Particulate organic material devoid of mineral residues and located on the soil surface.

Macroorganic matter Fragments of organic matter 20 μm to 50 μm in size (i.e., larger than the lower size limit of the sand fraction) contained within the mineral soil matrix and typically isolated by sieving dispersed soil.

Light fraction Organic materials isolated from mineral soils by flotation of dispersed soil suspensions on water or heavy liquids of densities 1.5 to 2.0 mg per m^3.

Dissolved organic matter Water-soluble organic compounds found in the soil solution that are smaller than 0.45 μm by definition; consists of simple compounds of biological origin (e.g., metabolites of microbial and plant processes) including sugars, amino acids, low molecular weight organic acids (citrate, malate, etc.); may also include large molecules.

Humus Organic materials remaining in the soil after removal of macroorganic matter and dissolved organic matter.

Non-humic biomolecules Identifiable organic structures that can be placed into discrete categories of biopolymers including polysaccharides and sugars, proteins and amino acids, fats, waxes and other lipids, and lignins.

Humic substances Organic molecules with chemical structures that do not allow them to categorized as nonhumic biomolecules.

Humic acids Organic materials that are soluble in alkaline solution but precipitate on acidification of the alkaline extracts.

Fulvic acids Organic materials that soluble in alkaline solution and remain soluble on acidification of the alkaline extracts.

Humins Organic materials that are insoluble in alkaline solution.

Inert organic matter Highly carbonized organic materials including charcoal, charred plant materials, graphites, and coals that have long turnover times

TABLE 7.24
Organic Matter Components of a Grassland Soil (wt% in dry matter)

Component	%
Humus	85
Plant roots	10
Soil flora and fauna	5
Total	100
Soil Flora and Fauna	**%**
Fungi and algae	40
Bacteria and actinomycetes	40
Earthworms	12
Other macrofauna	5
Mesofauna and microfauna	3
Total	100

TABLE 7.25
Interpretative Values for Organic Matter Content in Top 6 Inches of Soil

Soil Test Rating	Organic Matter Content Range (%)
Very low	0.1–1.5
Low	1.6–3.0
Medium	3.1–4.5
High	4.6–6.0
Very high	>6.0

7.8 SOIL SALINITY

7.8.1 Soluble Salt Determination Procedures

7.8.1.1 2:1 Water/Soil Extraction

Scoop 10 cm^3 2-mm-sieved soil into a beaker; add 20 mL water and stir thoroughly. Allow the suspension to settle at least 30 min or long enough for the solids to settle. Insert the conductivity cell into the supernatant and read the electrical conductivity.

7.8.1.2 1:1 Water/Soil Extraction

Scoop 20 cm^3 2-mm-sieved soil into a test tube or small container. Add 20 mL water, stir thoroughly, and allow the suspension to stand 15 to 20 min. Insert the conductivity cell into the suspension and read the electrical conductivity.

7.8.1.3 Saturated Paste Method

Weigh 250 g air-dried <10-mesh-sieved (2-mm) soil into a 400-mL beaker. Add water while stirring with a spatula until the soil slides freely from the surface of the spatula. At saturation the soil paste will glisten as it reflects light. Let stand for 1 hr. Transfer the saturated paste to a filter funnel and draw water from the soil by applying vacuum. Insert the conductivity cell into the filtrate and read the electrical conductivity.

TABLE 7.26
Interpretation of Soil Conductance Readings (dS/m)

Saturated Paste	2:1 Water/Soil	Effects
<1.0	<0.40	*Nonsaline*: Salinity effects mostly negligible.
1.1–2.0	0.40–0.80	*Very slightly saline*: Yields of very salt-sensitive crops may be reduced by 25 to 50%.
2.1–4.0	0.81–1.20	*Moderately saline*: Yields of salt-sensitive crops restricted; crop yields reduced by 25 to 50%.
4.0–8.0	1.21–1.60	*Saline soils*: Only tolerant crops will grow normally.
8.8–16.0	1.61–3.20	*Strongly saline*: Only salt-tolerant crops yield satisfactorily.
>16.0	>3.2	*Very strongly saline*: Only salt-tolerant crops will grow.

TABLE 7.27
Conductivity of Soluble Salts

Electrical Conductivity (dS/cm)[a]	Electrical Conductivity (dS/cm)[b]	Assessment
<0.6	0.0–2.0	Not saline
0.6–1.2	2.2–4.0	Slightly saline
1.2–2.4	4.1–8.0	Saline
2.4–6.0	8.1–16.0	Very saline
>6.0	>16.1	Highly saline

[a] *Handbook of Agriculture*, 1999, Marcel Dekker, New York.
[b] Jones, J.B., Jr., *Laboratory Guide for Conducting Soil Tests and Plant Analysis*, 2001, CRC Press, Boca Raton, FL.

TABLE 7.28
Relationship of Degree of Salinity (dS/m) and Soil Texture

	Soil Texture			
Degree of Salinity	Coarse to Loamy Sand	Loamy Fine Sand to Loam	Silt Loam to Clay Loam	Silty Clay Loam to Clay
Nonsaline	0–1.1	0–1.2	0–1.31	0–1.4
Slightly saline	1.2–2.4	1.3–2.4	1.4–2.5	1.5–2.8
Moderately saline	2.5–4.4	2.5–4.7	2.6–5.0	2.0–5.7
Strongly saline	4.5–8.9	4.8–9.4	5.1–10.0	5.8–11.4
Very strongly saline	>9.0	>9.5	>10.1	>11.5

TABLE 7.29
Interpretation of Field Soil Salt Concentrations

Salt Concentration		
ppm	dS/m	Safety Level
0–1,000	0–2	Low to normal
1,000–2,000		Slightly saline; some plants restricted
2,000–3,000		Moderately saline; many plants restricted
3,000–4,000		Strongly saline; salt-tolerant plants
>4,000	>16	Very strongly saline; few plants grow

Source: *Compost Organics: Buyers Guide*, *1997–1998*. Composting News, Mentor, OH.

TABLE 7.30
Crop Tolerance to Salinity

High Tolerance	Medium Tolerance
Bermuda grass	Sweet clover
Barley	Alfalfa
Sugar beet	Rye
Cotton	Wheat
	Oats
	Rice
	Sorghum
	Corn

7.8.2 Correcting Salinity Problems

7.8.2.1 Problem Soils

Sodium chloride (NaCl) toxicity is likely to occur in:

- Saline soils formed from salt water sediments
- Previously fertile soils that were flooded or heavily irrigated with water containing high concentrations of NaCl

7.8.2.2 Correcting Salinity[2]

Leaching with good quality irrigation water is the most effective means of removing excess Na and Cl from the soil. The water table may have to be lowered. Permeable soils such as well structured sandy soils are often easily reclaimed, but the problem is more difficult in less permeable soils (for example, poorly structured heavy clays).

If exchangeable Na in the soil is high, reclamation involves replacement of the adsorbed Na with Ca by applying gypsum (calcium sulfate), then leaching the dissolved Na and Cl beyond the rooting depths of the plants. If irrigation water is to be used to leach the Na, its quality should be checked before use to ensure it is not saline. Where excess NaCl cannot be wholly corrected by soil leaching, a more tolerant species may have to be grown.

TABLE 7.31
Amounts of Gypsum and Sulfur Required to Reclaim Alkali Soils

Exchangeable Na (meq/100 g)[a]	Tons/Acre for Top 1 ft		Tons/Acre for Top 6 in.	
	Gypsum	Sulfur	Gypsum	Sulfur
1	1.7	0.32	0.9	0.16
2	3.4	0.64	1.7	0.32
3	5.2	0.96	2.6	0.48
4	6.9	1.28	3.4	0.64
5	8.6	1.60	4.3	0.80
6	10.3	1.92	5.2	0.96
7	12.0	2.24	6.0	1.12
8	13.7	2.56	6.9	1.28
9	15.5	2.88	7.7	1.44
10	17.2	3.20	8.6	1.60

[a] As determined by soil test.

Source: U.S. Department of Agriculture, *Diagnosis and Improvement of Saline and Alkali Soils*, 1954, Handbook No. 60, U.S. Government Printing Office, Washington, D.C.

7.8.3 Measurement of Conductivity Using a Soluble Salt Meter*

7.8.3.1 Theory of Operation

Conductance is the readiness of materials to carry electric current. Liquids that carry electric currents are generally referred to as electrolytic conductors. The flow of current through electrolytic conductors is accomplished by the movement of electric charges (positive and negative ions) when the liquid is under the influence of an electrical field. The conductance of a liquid can be defined by its electrical properties — the ratio of current to voltage between any two points within the liquid. As the two points move closer together or further apart, the value changes. To be useful for analytical purposes, a measurement requires dimensions or physical parameters.

Defining the physical parameters of a measurement creates a standard measure. Specific conductance or conductivity is an example of a standard measure. It is defined as the reciprocal of the resistance in ohms measured between the opposing faces of a 1-cm cube of liquid at a specific temperature. The units used to define conductance are: 1 ohm = 1 mho = 1,000 mS = 1,000,000 µS. Standard international units may be used in place of mhos: 1 mho = 1 Siemen (S). Conductivity units are expressed as µS/cm (1.0 dS/m = 1.0 S/cm) or mS/cm.

7.8.3.2 Design of Conductivity Cell

In theory, a conductivity measuring cell is formed by two square surfaces spaced 1 cm apart. Cells of different physical configurations are characterized by a cell constant value known as K — a function of the electrode areas, the distance between the electrodes, and the electrical field pattern between the electrodes. This theoretical cell has a constant K of 1.0. Often, because of sample volume or space issues, a cell is designed differently. Cells with constants of 1.0 or more normally have small, widely spaced electrodes. Cells with constants of K = 0.1 or less normally have large, closely spaced electrodes. Since K reflects the configuraton of a certain cell, it must

* Information from Denton Slovacek, Manager of Technical Training Center, HACH Company, Loveland, CO.

be multiplied by the observed conductance to yield the actual conductivity reading. For example, for an observed conductance reading of 200 µS using a cell with K = 0.1, the conductivity value is 200 × 0.1 = 20 µS/cm.

In a simplified approach, the cell constant is defined as the ratio of the distance between electrodes (d) to the electrode area (A). This, however, neglects the fringe-field effect that affects the electrode area by the quantity AR. Therefore, K = d/(A + AR). Because it is normally impossible to measure the fringe-field effect and the amount of AR to calculate K, the actual K of a specific cell is determined by a comparison measurement of a standard solution of known electrolytic conductivity. The most commonly used standard solution for calibration is 0.01 *M* KCl which has a conductivity of 1,412 µS/cm at 25°C.

Some sources in literature quote this value at 1,409 or 1,413 µS/cm at 25°C. Differences are due to the use of kilograms (weights) of water rather than liters (volumes) and changes in assigned molecular weights, definitions of Siemens, the use of different temperature scales, and whether the inherent conductivity of water was subtracted from the equation. For normal laboratory calibration, the difference arising from using 1,409 versus 1,413 µS/cm is insignificant.

In summary, calibration of a conductivity probe is required to compensate for the fact that the K is not specifically known and changes as an electrode ages. Calibration simply adjusts the measured reading to the true value at a specified temperature.

7.8.3.3 Effect of Temperature

The conductivity of a solution with a specific electrolyte concentration will change with a change in temperature. The temperature-compensated conductivity of a solution is the conductivity the solution exhibits at the reference temperature. The reference temperature is 20 or 25°C. A measurement made at reference temperature needs no compensation. Generally, for most aqueous samples, a coefficient of 2.1% per degree Celsius (C) is used in temperature compensation, with the apparent value set 2.1% higher for each degree above 25°C. Conversely, the apparent value will be 2.1% lower for each degree below 25. For soil and irrigation water analysis, the standard temperature for measurement is 25°C. A useful algorithm for temperature correction is:

$$C = C_{25}[1 + 0.021(T - 25)]$$

where C = the measured conductivity of a solution at sample temperature; C_{25} = the conductivity of the solution at 25°C; and T = the sample temperature (in degrees C).

Many conductivity meters automatically compensate for temperature if the conductivity probe includes a thermistor. However, errors can arise in analysis if the thermistor is not accurate or the instrument is improperly calibrated.

The following examples explain the effects of and compensation for fringe-field effect and temperature.

Example 1: Manual Temperature Compensation —An analyst wishes to calibrate a conductivity probe and measure an unknown sample. The conductivity probe is specified to have a cell constant of 1.0. The analyst is calibrating in a 0.01*M* KCl (conductivity = 1,412 µS/cm at 25°C) solution at a temperature of 22°C. Automatic temperature compensation is not available.

1. Determine the conductivity of the 0.01*M* KCl at 22°C.

$$\text{Conductivity of KCl at 22°C} = 1{,}412[1 + 0.021(22–25)]$$

$$\text{Conductivity of KCl at 22°C} = 1{,}412\ [0.937]$$

$$\text{Conductivity of KCl at 22°C} = 1{,}323\ \mu\text{S/cm}$$

2. Immerse the conductivity probe into the standard and adjust the value to 1,323 µS/cm. Any adjustment made will compensate for the difference between the specified cell constants and the true cell constant.
3. The analyst measures an unknown sample whose temperature is 19°C and obtains an apparent value of 967 µS/cm. How is this value adjusted to 25°C?

$$967\ \mu S/cm = C_{25}\ [1 + 0.021(19–25)]$$

$$C_{25} = 967\ \mu S/[1 + 0.021(19–25)]$$

$$C_{25} = 967\ \mu S/[1 + 0.021(-6)]$$

$$C_{25} = 967\ \mu S/0.874$$

$$C_{25} = 1{,}106\ \mu S/cm$$

Example 2: Automatic Temperature Compensation (ATC) — An analyst wishes to calibrate a conductivity probe and measure a sample. The conductivity probe has a cell constant of 1.0. The analyst is calibrating in a 0.01*M* KCl (conductivity = 1,412 µS/cm at 25°C) solution at 22°C. ATC at 25°C is available.

1. Immerse the conductivity probe into the standard and adjust the value to 1,412 µS/cm. Any adjustment made will compensate for the difference between the specified cell constant and the true cell constant. (Most modern instrumentation displays the true temperature along with the temperature-compensated conductivity value.) In this case, the display would show a conductivity of 1,412 µS/cm and 22°C.
2. Once the electrode has been calibrated, it is cleaned and placed into the unknown sample at 19°C. When temperature is stable, the correct conductivity value of 1,106 µS is displayed.

7.8.3.4 Sources of Error in Measurement

7.8.3.4.1 Temperature Compensation

Because many conductivity probes now include a thermistor for ATC, it is important to determine whether the thermistor reading is accurate at the temperatures at which samples are measured. If it is not, the automatic temperature-corrected value will be inaccurate. Compare the measured value from the thermistor with that from a quality laboratory thermometer. If the values differ significantly, contact the manufacturer about the defect or consider manual temperature compensation.

7.8.3.4.2 Improper Calibration

Calibration standards often sit on laboratory shelves for long periods. They should be fresh and known to be correct at least to ±1% before calibration is attempted. Since the conductometric response is not perfectly linear at all ranges, it is best to calibrate the probe in the same magnitude of range as the samples to be measured. In other words, do not calibrate a conductivity probe in a 100-µS/cm standard if your samples are typically in the >1,000-µS/cm range. Standard conductivity solutions:

KCl Concentration at 25°C	Conductivity (µS/cm)
0.001*N*	0.147
0.010*N*	1.413
0.020*N*	2.767
0.050*N*	6.668

7.8.3.4.3 Condition of Probe

Probes can become inaccurate if the probe elements become coated with interfering substances. During normal use, rinse the probe thoroughly with laboratory grade water between each measurement. This will minimize the build-up of coating substances. If the probe needs cleaning, first try ethanol, which effectively removes most organics. If ethanol is not successful, clean the probe with a strong detergent solution and rinse thoroughly with demineralized water.

The cells may occasionally need replatinization to refresh the plates and return them back to the original cell constant. The cell constant will change when the platinum black layer becomes partially eroded or contaminated. Follow the manufacturer's directions on this procedure.

7.9 MEASUREMENTS AND CONVERSIONS

7.9.1 Electrical Conductivity Units and Conversions

1 millimho per centimeter = mmho/cm = conductivity x 10^{-3}
1 micromho per centimeter = µmho/cm = conductivity x 10^{-6}
1,000 micromhos per centimeter = 1 mmho/cm
1 millisiemen per centimeter = 1 mS/cm = 1 µmho/cm
1,000 microsiemen per centimeter = 1 µS/m = 1 µmho/cm
1 decasiemen per meter = 1 dS/m = 1 mS/cm = 1 mmho/cm = 700 ppm

7.9.2 Salinity (NaCl) and Alkalinity ($NaHCO_3$)

20-10-20 fertilizer (200 ppm) = conductivity of 1.5 dS/m and a pH of 5.6
100 ppm NaCl = conductivity of 3.0 dS/m
400 ppm NaCl = conductivity of 7.2 dS/m
100 ppm $NaHCO_3$ (pH = 6.06) = conductivity of 1.5 dS/m
200 ppm $NaHCO_3$ (pH = 7.14) = conductivity of 1.9 dS/m
300 ppm $NaHCO_3$ (pH = 7.43) = conductivity of 2.3 dS/m
400 ppm $NaHCO_3$ (pH = 7.62) = conductivity of 2.8 dS/m
500 ppm $NaHCO_3$ (pH = 7.88) = conductivity of 3.1 dS/m

REFERENCES

1. *Glossary of Soil Science Terms*, 1987, Soil Science Society of America, Madison, WI.
2. Grundon, N.J., *Hungry Crops: A Guide to Nutrient Deficiencies in Field Crops*, 1987, Queensland Department of Primary Industries, Brisbane, Australia.

Part IV

Soil Analysis and Treatment

8 Soil pH, Liming, and Liming Materials

8.1 DETERMINATION OF SOIL pH IN WATER AND SALT SOLUTIONS

8.1.1 Determination of pH in Water and Salt Solutions using pH Meter

8.1.1.1 Water pH Determination

Weigh 10 g air-dried <10-mesh-sieved (2-mm) soil into a cup.
Pipette 10 mL water into the cup and mix thoroughly for 5 min with a glass rod or mechanical stirrer.
Let the soil–water suspension stand for 30 min.
Perform pH measurement at 20 to 25°C (68 to 77°F).
Before analysis, stir the soil–water suspension with glass rod or mechanical stirrer.
Insert electrodes of calibrated pH meter into the soil–water slurry so that the electrode tips are at the soil–water interface; swirl soil–water suspension slightly.
Read pH immediately (after 30 to 60 sec) to the nearest 0.1 unit.

Note: Erratic movement of the pH meter dial or number may be due to a faulty operating electrode or lack of sufficient junction potential. The position of the reference electrode with respect to the glass electrode and the flow rate from the reference electrode may affect the pH determination.

8.1.1.2 pH Determination in 0.01*M* Calcium Chloride ($CaCl_2$)

To mask the variability in salt content, maintain the soil in a flocculated condition, and decrease the junction potential effect. Measure the soil pH in 0.01*M* $CaCl_2$ solution. The same procedure is followed as used to measure pH in water, except 0.01*M* $CaCl_2$ is substituted for water in preparing the soil slurry. The pH values obtained will be lower (usually 0.3 to 0.5 of a pH unit) than values measured in water. The pH meter needle will move less with agitation of the slurry and quickly settle on the reading. A different set of interpretative values must be used when pH is measured in 0.01*M* $CaCl_2$.

8.1.1.2.1 Reagents

0.01*M* Calcium chloride — Weigh 1.47 g calcium chloride dihydrate ($CaCl_2{\cdot}2H_2O$) into a 1,000-mL volumetric flask and bring to volume with water.
1.0*M* Calcium chloride — Weigh 147 g calcium chloride dihydrate ($CaCl_2{\cdot}2H_2O$) into a 1,000-mL volumetric flask and bring to volume with water.

8.1.1.2.2 pH Determination

Weigh 5 g or scoop 4.25 cm^3 air-dried <10-mesh-sieved (2-mm) soil into a 50-mL cup.
Pipette 5 mL 0.01*M* $CaCl_2$ solution into the cup and stir 30 min on a mechanical stirrer or shaker or stir periodically with a glass rod for 30 min.
Calibrate the pH meter according to the instructions supplied with the meter.
Stir the soil and 0.01*M* $CaCl_2$ slurry.

Lower the electrodes into the soil–$CaCl_2$ slurry so that the electrode tips are at the soil–water interface.
While stirring the slurry, read the pH and record value to the nearest 0.1 pH unit.

Note: For laboratories desiring tests in water and 0.01*M* $CaCl_2$, 5 mL water can be substituted for the 5 mL 0.01*M* $CaCl_2$. After the water pH is detertmined, add 1 drop 1*M* $CaCl_2$ to the soil–water suspension, stir or shake 30 min and then read the pH of the suspension.

8.1.1.3 pH Determination in 1*N* Potassium Chloride (KCl)

To establish a significant salt content in the soil slurry for measuring pH, the soil pH measurement can be made in a 1*N* KCl solution. This procedure is commonly used in Europe and other parts of the world for soil pH determination. The same procedure is followed as that used to measure pH in water, except 1*N* KCl is substituted for water in the preparation of the soil slurry. The pH value obtained will be lower (usually 0.5 to 1.0 of a pH unit) than that measured in water. The pH meter needle will move less with agitation in the soil slurry and quickly settle on the reading. A different set of pH interpretative values must be used when the pH is measured in 1*N* KCl.

8.1.1.3.1 Reagent

1*N* Potassium chloride — Weigh 74.56 g potassium chloride (KCl) into a 1,000-mL volumetric flask and bring to volume with water.

8.1.1.3.2 pH Determination

Weigh 5 g or scoop 4.25 cm^3 air-dried <10-mesh-sieved (2-mm) soil into a cup.
Pipette 5 mL 1 *N* KCl into the cup and stir for 5 sec.
Let stand 10 min.
Calibrate the pH meter according to the instructions supplied with the meter.
Stir the soil and 1*N* KCl slurry.
Lower the electrodes into the slurry so that the electrode tips are at the soil–water interface.
Read the pH and record to nearest 0.1 pH unit.

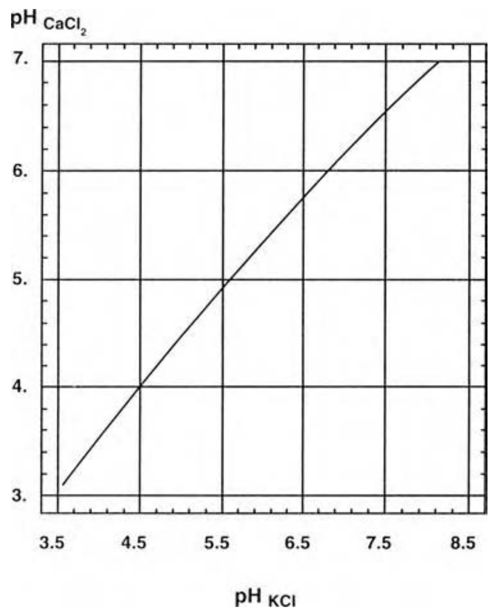


FIGURE 8.1 Regression line for the relationship of pH of $CaCl_2$ and pH of KCl.

8.1.2 Determination of Soil pH Using Color Indicators

pH and Corresponding Colors of Various Indicators

Critical Indicator	Critical pH	Color Change[a]
Thymol blue[b]	1.9	R-O-Y
Dinitrophenol	3.1	C-Y-Y
Methyl orange	3.7	R-Y-O
Bromphenol blue	4.0	Y-Pu-V
Bromcresol green	4.6	Y-G-B
Chlorphenol red	5.6	Y-OP-V
Methyl red	5.7	R-O-Y
Bromthymol blue	6.9	Y-G-B
Phenol red	7.3	Y-RO-V
Phenolphthalein	8.3	C-P-P
Thymolphtalein	9.4	C-B-B
Alizarin yellow R	10.3	Y-O-R

[a] Color at center is at critical pH; B = blue, C = colorless, G = green, O = orange, P = pink, Pu = purple, R = red, V = violet, Y = yellow.
[b] Thymol blue has two critical pH values.

pH and Corresponding Color of Bromocresol Purple Mixed Indicator

Color	pH
Brilliant red	<3.0
Red	3.1–4.0
Red orange	4.1–4.7
Orange	4.8–5.2
Orange yellow	5.3–5.7
Yellow	5.8–6.1
Greenish yellow	6.2–6.4
Green	6.8–7.3
Greenish blue	7.4–7.8
Blue	>7.9

8.1.2.1 Procedures

8.1.2.1.1 Laboratory Procedure

Weigh 15.0 g aliquot of soil into a clean 100-mL centrifuge tube. Add 30 mL distilled water, and swirl frequently for 1 min. Centrifuge the mixture at 2,500 rpm for 15 min and filter the supernatant into a 150-mL beaker. Transfer 10 mL of the clear solution into a test tube. Add 5 to 10 drops duplex indicator or mixed indicator and swirl to develop color. Match the color with the color chart to determine pH. If the mixed indicator is used, prepare a series of standards and match the color with the standards.

8.1.2.1.2 Field Procedure

Place a small sample of soil in a plastic spoon. Wet the sample with distilled water and allow the mixture to react for 5 min. Tilt the spoon to separate the liquid from the soil and add 2 to 3 drops of duplex indicator (Bromocresol Purple) to the solution. Match the color developed with the color chart to determine pH.

8.2 SOIL ACIDITY DEFINITIONS

Acid soil Soil with a pH value <7.0.

Acidic cations Hydrogen ions (H^+) or cations that, when added to water, undergo hydrolysis and produce an acidic solution. Examples in soils are H^+, Al^{3+}, and Fe^{3+}.

Acidity, residual Soil acidity that is neutralized by lime or other alkaline materials; it cannot be replaced by an unbuffered salt solution.

Acidity, salt-replaceable Al or H that can be replaced from an acid by an unbuffered salt solution such as KCl or NaCl.

Acidity, total Total acidity in a soil or clay; usually estimated by a buffered salt determination: cation exchange capacity – exchangeable bases = total acidity; can also be approximated by: salt-replaceable acidity + residual acidity.

8.3 pH Interpretation

The degree of acidity or alkalinity is expressed as a pH value; descriptive terms related to a range in pH serve as interpretations. The "ideal" soil pH and range will also vary with soil type and crop. Independent of these factors, three such category ranges for soil–water pH categorization are shown in Table 8.1.

TABLE 8.1
Three Category Ranges of Soil–Water pH Interpretation

Category	pH	Category	pH	Category	pH
Extremely acid	<4.5	Very acid	4.5–5.5	Acid	<4.5
Very strongly acid	4.5–5.0	Acid	5.6–6.0	Weakly acid	4.5–6.5
Strongly acid	5.1–5.5	Slightly acid	6.1–6.8	Neutral	6.6–7.5
Moderately acid	5.6–6.0	Neutral	6.9–7.6	Weakly basic	7.6–9.5
Slightly acid	6.1–6.5	Alkaline	7.7–8.3	Basic	>9.5
Neutral	6.6–7.3				
Slightly alkaline	7.4–7.8				
Moderately alkaline	7.9–8.4				
Strongly alkaline	8.5–9.0				
Very strongly alkaline	>9.1				

TABLE 8.2
Interpretation of Soil–Water pH

pH	Interpretation
<4.0	Extremely acid
4.0–5.0	Very strongly acidic
5.0–5.5	Strongly acid
5.5–6.0	Moderately acidic
6.0–6.7	Slightly acidic
6.7–7.3	Range of neutral
7.0	Neutral
7.3–8.0	Weakly alkaline
8.0–8.5	Moderately alkaline
8.5–9.0	Highly alkaline
9.0–10.0	Very highly alkaline
>10.0	Extremely alkaline
6.0–7.5	Optimal for most crops
5.0–7.0	Subhumid grassland soils
7.5–8.5	Soils with excess Ca^{2+} ion
8.0–10.0	Soils with excess Na^{+} ions

Source: *Handbook of Agriculture*, 1999, Marcel Dekker, New York. With permission.

TABLE 8.3
pH Categories Determined in 0.01*M* $CaCl_2·2H_2O$

Category	pH
Acid	<4.5
Weakly acid	4.5–6.5
Neutral	6.5–7.5
Weakly basic	7.5–9.5
Basic	>9.5

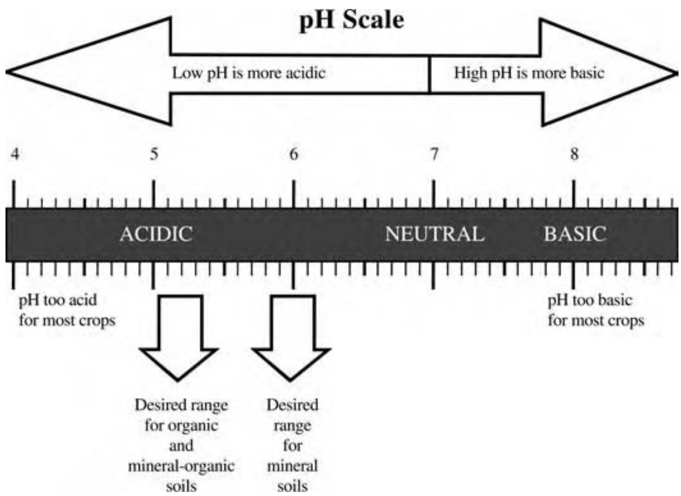


FIGURE 8.2 pH scale for agricultural soils. (*Source*: *Crop Fertilization Based on North Carolina Soil Tests*, 1997, North Carolina Department of Agriculture and Consumer Services, Raleigh.)

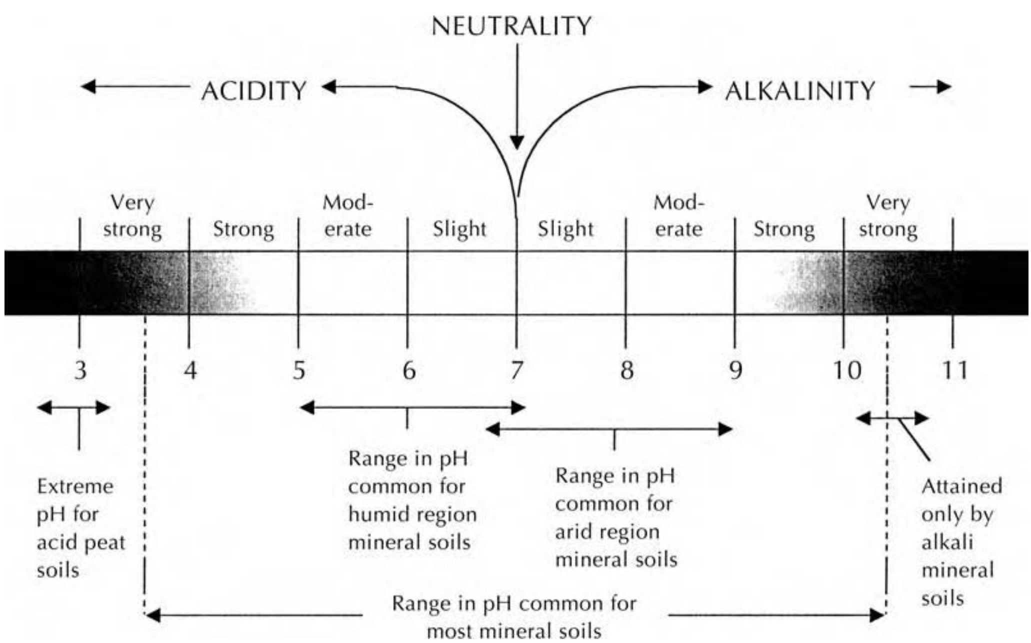


FIGURE 8.3 Soil pH ranges. (*Source*: *Soil Analysis: An Interpretation Manual*, 1999, CSIRO Publishing, Collingwood, Australia.)

8.4 EFFECT OF pH ON SOIL AND PLANT COMPOSITION

Soil pH can significantly influence plant growth by affecting the composition of the soil solution and the availability (sufficiency or toxicity) of essential and nonessential elements as shown in Figure 8.4 for mineral soils, Figure 8.5 for organic soils, and Table 8.4.

TABLE 8.4
Effect of Soil pH on Element Availability and/or Soil Solution Composition

Element	pH Decreasing	pH Increasing
Aluminum	Increases	Decreases
Copper	Increases	Decreases
Iron	Increases	Decreases
Magnesium	Decreases	Increases
Manganese	Increases	Decreases
Zinc	Increases	Decreases

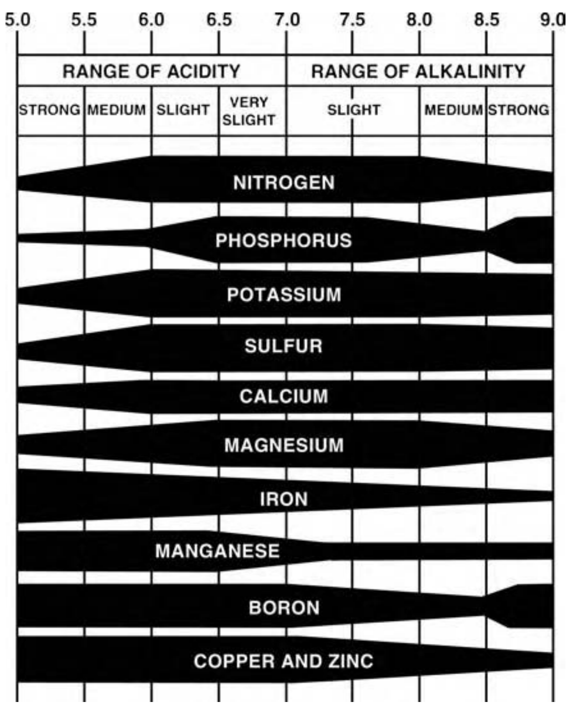


FIGURE 8.4 Availability of elements to plants at different pH levels for mineral soils. (From Sartoretto, P., *The pH-Factor*, 1991 W-A-clearly Chemical, Dayton, N.J.).

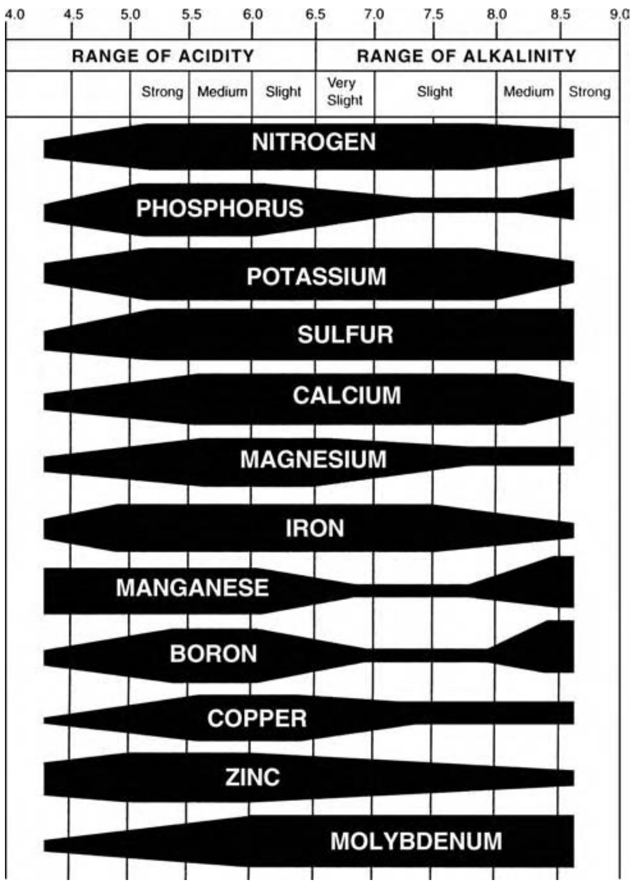


FIGURE 8.5 Availability of elements to plants at different pH levels for mineral soils. (From Sartoretto, P., *The pH-Factor*, 1991 W-A-clearly Chemical, Dayton, N.J.).

8.5 FERTILIZER EFFICIENCY

TABLE 8.5
Fertilizer Efficiency (%) at Varying Soil pH Levels

Soil Acidity	pH	Fertilizer Efficiency (%) Nitrogen	Phosphate	Potash
Extreme	4.5	30	23	33
Very strong	5.0	33	34	52
Strong	5.5	77	46	77
Medium	6.0	89	52	100
Neutral	7.0	100	100	100

8.6 LIME RATE (LR) RECOMMENDATIONS

The lime requirement (LR) is the quantity of agricultural limestone required to raise the soil–water pH from acidic level to a level near neutrality. Determining the soil–water pH and knowing the soil texture (plus organic matter content for some types of soil) allows LR to be estimated. Several buffer methods are commonly used to determine soil LR levels: the Adams–Evans buffer for sandy low cation exchange capacity (CEC) soils, SMP for silt and clay loam soils of moderate CEC and organic matter content, and the Mehlich buffer for most soils.[1]

TABLE 8.6
Finely Ground Limestone Needed to Raise pH from 4.5 to 5.5 and from 5.5 to 6.5 in a 7-Inch Layer of Soil

	Limestone Requirement Per Acre			
	Cool and Temperate Regions[a]		Warm and Tropical Regions[b]	
Soil Type	pH 4.5–5.5	pH 5.5–6.5	pH 4.5–5.5	pH 5.5–6.5
Sand, loamy sand	0.5	0.5	0.3	0.4
Sandy loam	0.8	1.3	0.5	0.7
Loam	1.2	1.7	0.8	1.0
Silt loam	1.5	2.0	1.2	1.4
Clay loam	1.9	2.3	1.5	2.0
Muck	3.8	4.3	3.3	3.8

[a] Gray or brown Podsols.
[b] Red or yellow soils.

TABLE 8.7
Approximate Amounts (tons/A) of Finely Ground Limestone Needed to Raise the pH of a 7-Inch Layer of Soil

	Limestone Requirement LR(tons/A) to Increase pH		
Soil Region and Texture Class	From 3.5 to 4.5	From 4.5 to 5.5	From 5.5 to 6.5
Soils of warm-temperate and tropical regions			
Sand and loamy sand	0.3	0.3	0.4
Sandy loam	—	0.5	0.1
Loam	—	0.8	1.0
Silt loam	—	1.2	1.4
Clay loam	—	1.5	2.0
Muck	2.5	3.3	3.8
Soils of cool-temperate and temperate regions			
Sand and loamy sand	0.4	0.5	0.6
Sandy loam	—	0.8	1.3
Loam	—	1.2	1.1
Silt loam	—	1.5	2.0
Clay loam	—	1.9	2.3
Muck	2.9	3.8	4.3

TABLE 8.8
Quantity of Ag-Ground Limestone (1,000 lb/acre)[a] Required to Raise Acid Soil pH to 6.5 to a Soil Depth of 6 2/3 Inches Based on Soil–Water pH and Soil Texture

	Lime Requirement (1,000bs/A)[b]				
Soil–Water pH	**S**	**SL**	**L**	**SiCl**	**O**
3.5–3.9	4.0	6.5	9.0	12.0	20.0
4.0–4.4	3.0	5.0	7.0	9.0	15.0
4.5–4.9	2.0	3.5	5.5	6.5	10.0
5.0–5.4	1.5	2.3	4.0	5.0	5.0
5.5–5.9	1.0	1.5	2.5	3.5	nr[c]
6.0–6.4	0.5	1.0	1.5	2.5	nr

[a] Ag-ground limestone with a Total Neutralizing Power (TNP) of 90 and fineness of 40%, <100-mesh; 50%, <60-mesh; and 95%, <8-mesh. Rate adjustment is required for other liming materials or different depths.
[b] S = sand; SL = sandy and gravelly loam; L = loam; SiCl = silt and clay loam; O = organic soil and soilless mixes.
[c] nr = None required.

TABLE 8.9
Approximate Amount of Finely Ground Limestone Needed to Raise the pH of a 7-Inch Layer of Soil

	LR (lb/1,000 ft^2) to Raise pH	
Soil Texture	**From 4.5 to 5.5**	**From 5.5 to 6.5**
Sand and loamy sand	23	28
Sandy loam	37	60
Loam	55	78
Silt loam	69	92
Clay loam	87	106
Muck	174	197

Source: *Western Fertilizer Handbook*, *Horticulture Edition,* Interstate Publishers, 1998, Danville, IL. With permission from California Plant Health Association.

TABLE 8.10
Agricultural Limestone (Tons/Acre) Needed to Raise Soil pH to Desired Level Based on the SMP Lime Test Index and Incorporation Depth of 8 In.

Lime Test Index[a]	Desired pH Level				
	Mineral Soils			Organic Soils	
	6.8[b]	6.5[b]	6.0[b]	Soil pH	5.3
68	1.4	1.2	1.0	5.2	0.0
67	2.4	2.1	1.7	5.1	0.7
66	3.4	3.0	2.4	5.0	1.3
65	4.5	3.8	3.1	4.9	2.0
64	5.5	4.7	3.9	4.8	2.6
63	6.5	5.6	4.6	4.7	3.2
62	7.5	6.5	5.3	4.6	3.9
61	8.6	7.3	6.0	4.5	4.5
60	9.6	8.2	6.7	4.4	5.1

[a] Lime test index is the SMP buffer pH x 10.
[b] Values based on agricultural limestone with a neutralizing value of 90% (Indiana RNV = 65, 0hio total neuitralizing power = 90+). Adjustments in the application rate should be made for liming materials with different particle sizes, neutralizing values, and depths of incorporation.

TABLE 8.11
Adjustment for Extractable Aluminum (based on Morgan–Wolf modification)

Add 45 lb ag-ground limestone/acre for each 10 ppm extractable Al.

TABLE 8.12
Prediction of Lime Requirement for Most Tropical Soils

$CaCO_3$, equivalent (tons/ha) = 2.0[a] x meq Al/100 g

[a] Factor ranges from 1.5 to 3.3, with most between 1.5 and 2.0; actual value determined in accordance with site specificity and crop tolerance to Al.

Source: *International Soil Fertility Manual*, 1995, Potash & Phosphate Institute, Norcross, GA.

8.7 LIMING GLOSSARY

Acid-forming fertilizer Fertilizer capable of increasing acidity (lowering pH) of a soil after application.

Agricultural liming material Material that contains Ca and Mg in forms capable of reducing soil acidity.

Aglime Synonymous with agstone; produced by crushing and grinding calcite or dolomite limestone to a gradation or fineness that enables it to neutralize soil acidity; usually ground to pass sieves in the 8- to 100-mesh range or finer.

Calcite Crystalline form of calcium carbonate ($CaCO_3$). Pure calcite contains 100% calcium carbonate (40% Ca). Although calcite occurs in nature, limestones of this purity are not commercially available. It may be colorless, but is usually tinted by impurities.

Calcitic limestone Term widely used to refer to agricultural limestone with high Ca content; mainly contains $CaCO_3$, but may also contain small amounts of Mg. Term is not restrictive in definition like *calcite* with which it is frequently confused.

Calcium carbonate ($CaCO_3$) A compound consisting of Ca combined with carbonate; occurs in nature as limestone, marble, chalk, marl, shell, and similar substances.

Calcium carbonate equivalent (CCE) Expression of the acid-neutralizing capacity of a carbonate relative to that for pure $CaCO_3$, e.g., calcite; expressed as a percentage. The value for pure calcite is 100%; for pure dolomite, 108.5%. CCEs of most limestones vary from these percentages due to impurities in the rock and the fact that commercially available limestones are usually composed of mixtures of calcite and dolomite rather than either compound in its pure form.

Calcium oxide (CaO) Chemical compound composed of Ca and O; formed from $CaCO_3$ by heating limestone to drive off CO_2; also known as quick lime, unslaked lime, burnt lime, caustic lime; does not occur in nature.

Calcium oxide equivalent Percentage of calcium oxide (CaO) in a liming material plus 1.39 times the magnesium oxide (MgO) content. For pure calcite, the value is 56.0%; for pure dolomite, 60.8%. Used by some states as a measure of aglime quality.

Dolomite Limestone containing $MgCO_3$ in an amount approximately equivalent to its $CaCO_3$ content. Limestone containing $MgCO_3$ in lesser proportions is called magnesium limestone or dolomitic limestone. Pure dolomite is 54.3% $CaCO_3$ and 45.7% $MgCO_3$. Expressed another way, it is comprised of 30.4% CaO, 21.8% magnesia (MgO), and 47.8% CO_3.

Dolomitic limestone Limestone that contains from 10% up to, but less than, 50% dolomite, and from 50 to 90% calcite. The magnesium carbonate ($MgCO_3$) content of dolomitic limestone may range approximately from 4.4 to 22.6%.

Effective calcium carbonate equivalent (ECCE) Expression of aglime effectiveness based on the combined effect of purity (CCE) and fineness; required for labeling in some states; determined by multiplying CCE by a set of factors based on fineness of grind of the limestone; also referred to as effective neutralizing value (ENV), total neutralizing power (TNP), effective neutralizing power (ENP), effective neutralizing material (ENM) and, in one state, as lime score.

Gypsum Hydrated form of calcium sulfate ($CaSO_4$); supplies calcium to soil, but is neutral and does not correct soil acidity; hence, it is not a liming material.

Lime Chemically, it is a compound comprised of calcium and magnesium oxides produced by calcining calcitic or dolomitic limestone; that is, replacing the carbonate (CO_3^{2-}) ion with oxygen under heat. However, the term is also broadly applied in agriculture to any material containing calcium and magnesium in forms capable of correcting soil acidity.

Lime requirement Quantity of agricultural limestone required to bring an acid soil to neutrality or some other desired degree of acidity or pH; usually stated in pounds per acre of $CaCO_3$ needed to bring the soil to the desired pH under field conditions.

Magnesium limestone Limestone containing 5 to 10% dolomite and 90 to 95% calcite. The $MgCO_3$ content of magnesium limestone may range from 2.3 to 4.4%.

Magnesium carbonate Compound consisting of Mg combined with CO_3; occurs in nature as magnesite and as a constituent of dolomitic limestone and dolomite.

Magnesium oxide (MgO) Chemical compound composed of Mg and O; formed from $MgCO_3$ by heating to drive off CO_2, or in a mixture with CaO by heating magnesium limestone or dolomite; also known as magnesia, it is found in nature as periclase.

Marble Compact, hard, polishable form of limestone.

Marl Granular or loosely consolidated, earthy material composed largely of $CaCO_3$ in theform of sea shell fragments; contains varying amounts of silt and organic matter.

Neutralizing power Calculated on the basis of the chemical composition and fineness of a liming material.

Pelletized lime Produced by binding or compressing fine lime particles into large granules or pellets.

Suspension lime Suspended finely ground aglime, 100- to 200-mesh, in 50:50 lime:water suspension.

8.8 AGLIME MATERIALS AND CHARACTERISTICS

TABLE 8.13
Common Liming Materials[a]

Name	Chemical Formula	Equivalent % $CaCO_3$	Source
Shell meal	$CaCO_3$	95	Natural shell deposits
Limestone	$CaCO_3$	100	Pure form, finely ground
Hydrated lime	$Ca(OH)_2$	120–135	Steam burned
Burned lime	CaO	150–175	Kiln burned
Dolomite	$CaCO_3{\cdot}MgCO_3$	110	Natural deposit
Sugar beet lime[b]	$CaCO_3$	80–90	Sugar beet by-product
Calcium silicate	$CaSiO_3$	60–80	Slag
Power plant ash	CaO, K_2O, MgO, Na_2O	5–50	Wood-fired power plants
Cement kiln dust	CaO, $CaSiO_3$	40–60	Cement plants

[a] Ground to same degree of fineness and at similar moisture content.
[b] Contains 4 to 10% organic matter.

Source: Western Fertilization Handbook, *Horticulture Edition,* 1998, Interstate Publishers, Danville, IL. With permission from California Plant Health Association.

TABLE 8.14
Calcium Carbonate Equivalents (CCEs) of Aglime Materials

Aglime Material	CCE (%)
Calcium carbonate	100
Calcitic limestone	85–100
Dolomitic limestone	95–108
Marl (Selma chalk)	50–90
Calcium hydroxide (slaked lime)	120–135
Calcium oxide (burnt or quick lime)	150–175
Calcium silicate	86
Basic slag	50–70
Ground oyster shells	90–100
Cement kiln dusts	40–100
Wood ashes	40–50
Power plant ashes	25–50

TABLE 8.15
Amounts of Aglime Materials at Different $CaCO_3$ Equivalents Required to Equal 1 Ton Pure $CaCO_3$

$CaCO_3$ Equivalent of Liming Material (%)	lb Needed to Equal 1 Ton Pure $CaCO_3$
60	3,333
70	2,857
80	2,500
90	2,222
100	2,000
105	1,905
110	1,818
120	1,667

TABLE 8.16
Effect of Fineness on Aglime Availability

	Years after Application	
Mesh Size	1	4
Coarser than 8	5	15
8 to 20	20	45
20 to 50	50	100
50 to 100	100	100

TABLE 8.17
Adjustment of LR Based on Depth of Incorporation

Depth of Incorporation (in.)	Multiplication Factor
3	0.43
4	0.57
5	0.71
6	0.86
7	1.00
8	1.14
9	1.29
10	1.43
11	1.57
12	1.71

TABLE 8.18
Aglime Material $CaCO_3$ Equivalents Required to Equal 1 Ton Pure $CaCO_3$

$CaCO_3$ Equivalent of Liming Material (%)	lb Needed to Equal 1 Ton Pure $CaCO_3$
60	3,333
70	2,857
80	2,500
90	2,222
100	2,000
105	1,905
110	1,818
120	1,667

8.9 LOWERING SOIL–WATER pH

TABLE 8.19
Approximate Amounts of S (95%) Needed to Increase Acidity of a 6-Inch-Deep Layer of a Carbonate-Free Soil

	lb S/1,000 Ft^2		
Change in pH Desired	Sand	Loam	Clay
8.5 to 6.5	45.9	57.4	68.8
8.0 to 6.5	27.5	34.4	45.9
7.5 to 6.5	11.5	18.4	23.0
7.0 to 6.5	2.3	3.4	6.9

Source: *Western Fertilizer Handbook, Horticultural Edition*, 1990, Interstate Publishers, Danville, IL. With permission from California Plant Health Association.

TABLE 8.20
Commonly Used Materials and Equivalent Amendment Values

Material (100% Basis)	Chemical Formula	lb Amendment Equivalent to 100 lb Pure Gypsum	lb Amendment Equivalent to 100 lb Soil S
Gypsum	$CaSO_4 \cdot 2H_2O$	100	538
Soil sulfur	S	19	100
Concentrated sulfuric acid	H_2SO_4	61	320
Ferric sulfate	$Fe_2(SO_4)_3 \cdot 9H_2O$	109	585
Lime sulfur (22% S)	CaS	68	365
Calcium chloride	$CaCl_2 \cdot H_2O$	86	—
Calcium nitrate	$Ca(NO_3)_2 \cdot H_2O$	106	—
Aluminum sulfate	$Al_2(SO_4)_3 \cdot 18H_2O$	129	694
Ammonium polysulfide	$(NH_4)_2S_x$	4	23

Source: *Western Fertilizer Handbook*, *Horticulture Edition,* 1990, Interstate Publishers, Danville, IL. With permission from California Plant Health Association.

8.10 RESULTS OF NORTH AMERICA SOIL TESTS

The following table shows results of soil analyses performed on approximately 2.5 million samples collected in Fall 2000 and Spring 2001 by 31 private and 34 public laboratories.

TABLE 8.21
Cumulative Relative Frequencies (%) for Soil Test Water pH in North America by Region

Water pH (1:1)								
5.0	**5.1–5.5**	**5.6–6.0**	**6.1–6.5**	**6.6–7.0**	**7.1–7.5**	**7.6–8.0**	**8.1–8.5**	**>8.5**
North Central (994,652 Samples)								
2	8	27	56	80	92	98	100	100
Northeast (45,327 Samples)								
5	16	42	73	93	99	100	100	100
Northern Great Plains (124,057 Samples)								
0	2	8	18	33	52	82	98	100
Southeast (848,258 Samples)								
7	20	48	72	88	97	99	100	100
Southern Great Plains (221,718 Samples)								
4	15	31	48	62	75	90	99	100
West (91,249 Samples)								
2	7	12	20	31	46	71	96	100

Notes: Regional category averages are means of state or province percentages and are not weighted by number of samples.
North Central: Missouri, Ohio, Kentucky, Illinois, Indiana, Iowa, Michigan, Wisconsin, Minnesota.
Northeast: Prince Edward Island, New Brunswick, Maine, Massachusetts, Delaware, Quebec, New Hampshire, Maryland, Connecticut, New Jersey, Nova Scotia, Pennsylvania, New York, Vermont.
Northern Great Plains: Alberta, Manitoba, South Dakota, Saskatchewan, North Dakota, Montana.
Southeast: North Carolina, South Carolina, Alabama, Florida, Mississippi, Louisiana, Georgia, Tennessee, Virginia, Arkansas.
Southeast: Oklahoma, Nebraska, Texas, Kansas.
West: Oregon, Washington, Califonia, Colorado, Nevada, New Mexico, Idaho, Utah, Arizona, Wyoming.

Source: Soil Test Levels in North America: Summary Update, PPI/PPIC/FAR Technical Bulletin 2001–1, Potash & Phosphate Institute, Norcross, GA. With permission.

REFERENCES

1. Jones, J. B., Jr., 2001, *Laboratory Guide for Conducting Soil Tests and Plant Analysis*, CRC Press, Boca Raton, FL.

9 Fertilizers

9.1 INTRODUCTION

Farmers worldwide now use 10 times more fertilizer than was used in 1950. Nutrient element depletion of the principal nutrient elements (N, P, and K) ranges from 40 to 60 kg per ha in Latin America and some parts of Africa. World fertilizer use totaled 141 million tons in 2000 (86 million tons of N, 33 million tons of P, and 22 million tons of potash. World fertilizer use between 1950 and 2000 peaked in 1989, decreased steadily from 1989 to 1995, and then began to increase (see Figure 9.1).

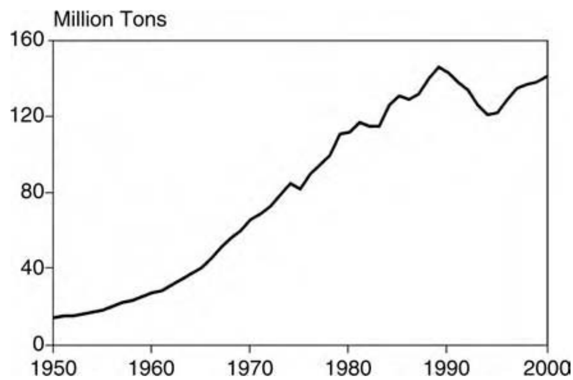


FIGURE 9.1 World fertilizer use, 1950–1996. (*Source*: Worldwatch Paper 136, *The Agricultural Link, 1997*, Worldwatch Institute, Washington, D.C.)

Low fertilizer prices tended to stimulate fertilizer use. In recent years, use increased in most developing countries and remained about the same or slightly decreased in the developed world. Africa uses only 2% of the world's fertilizer tonnage — a quantity insufficient to replace what is removed by crops that undermine soil fertility. The low rate of use is due to lacks of transport infrastructure, credit, and agronomic advisors. The recent reduction in world grain stocks may lead to increased fertilizer use.

Fertilizer is defined as an "organic or inorganic material of natural or synthetic origin (other than liming materials) that is added to a soil to supply one or more elements essential to the growth of plants." This section will discuss fertilizer use, terminology, materials, and application.

9.2 FERTILIZER USE

TABLE 9.1
World Fertilizer Use, 1950–2000

Year	Total (million tons)	kg/Person
1950	14	5.5
1955	18	6.5
1960	27	8.9
1965	40	12.0
1970	66	17.8
1971	69	18.2
1972	73	18.9
1973	79	20.1
1974	85	21.2
1975	82	20.1
1976	90	21.6
1977	95	22.4
1978	100	23.2
1979	111	25.3
1980	112	25.1
1981	117	25.8
1982	115	24.9
1983	115	24.5
1984	126	26.4
1985	131	27.0
1986	129	26.1
1987	132	26.3
1988	140	27.4
1989	146	28.1
1990	143	27.1
1991	138	25.7
1992	134	24.6
1993	126	22.8
1994	121	21.6
1995	122	21.4
1996	129	22.4
1997	135	23.1
1998	137	23.1
1999	139	23.0
2000[a]	141	23.2

[a] Preliminary.

Sources: Fertilizer Yearbook, United Nations Food and Agriculture Organization, Rome, various years; Soh and Prud'homme, *Fertilizer Consumption Report*; World and Regional Overview and Country Reports, International Fertilizer Association, Paris, December 2000.

TABLE 9.2
Fertilizer Consumption by Region for 1995 and Projected Growth Rates for 2025 and 2050

Region	Consumption (million tons)			Growth Rate (%)	
	1995	2025	2050	1995–2025	2025–2050
Africa	4	13	30	4.4	3.5
China	32	42	43	1.0	0.1
Latin America	9	20	30	2.6	1.6
Middle East	2	6	6	2.9	0.4
Southern and Southeast Asia	24	51	64	2.6	0.9
Eastern Europe	3	5	6	2.2	0.7
Former Soviet Union	5	13	17	3.7	0.9
North America	22	26	28	0.7	0.3
Pacific OECD[a]	4	4	3	0.3	–1.1
Western Europe	20	24	23	0.7	–0.3
Developing	71	132	174	2.1	1.1
Transitional	7	19	23	3.2	0.9
OECD[a]	45	205	251	1.7	0.0
World Total	123	205	251	1.7	0.8

[a] OECD = Organization for Economic Cooperation and Development.

TABLE 9.3
Field Crops: Percent of Area Receiving Fertilizer Applications, All States Surveyed, 1995–1999[a]

Crop	Nitrogen	Phosphate	Potash
		%	
	1995		
Corn	97	81	70
Cotton, upland	87	56	40
Soybeans	17	22	25
Wheat, winter	86	54	16
Wheat, durum	92	78	10
Wheat, other spring	87	78	23
	1996		
Corn	98	85	73
Cotton, upland	77	55	43
Soybeans	15	25	27
Wheat, winter	86	51	6
Wheat, durum	93	73	8
Wheat, other spring	89	79	24
	1997		
Corn	99	84	72
Cotton, upland	90	67	58
Soybeans	20	26	33
Wheat, winter	84	53	15
Wheat, durum	95	77	8
Wheat, other spring	92	82	25
	1998		
Corn	98	63	66
Cotton, upland	84	66	53
Soybeans	17	24	27
Wheat, winter	89	63	22
Wheat, durum	94	76	5
Wheat, other spring	87	77	25
	1999		
Corn	98	82	67
Cotton, upland	86	59	52
Soybeans	18	26	28

[a] Acres receiving one or more applications of a specific fertilizer ingredient.

Source: National Agriculture Statistics Service, Washington, D.C., 2001.

9.3 FERTILIZER GLOSSARY[1,2]

Acid-forming A product that tends to make soil more acid.

Acid-forming fertilizer Fertilizer that, after application to and reaction with soil, increases residual acidity and decreases soil pH.

Ammonia See *anhydrous ammonia* and *aqua ammonium.*

Ammoniated superphosphate Product formed by reaction of superphosphate with ammonia (NH_3).

Ammoniation Process by which anhydrous ammonia, aqua ammonia or a solution containing NH_3 or other form of nitrogen is used to form ammoniated superphosphate or treat a mixture of fertilizer ingredients (including superphosphate) in the manufacture of a multiple nutrient element fertilizer.

Ammonium hydroxide (NH_4OH) See *aqua ammonia*.

Ammonium nitrate (NH_4NO_3) Product containing approximately 33.5% nitrogen, half of which is in the ammonium (NH_4) form and the other half in the nitrate (NO_3) form. Ammonium nitrate is water soluble and is used in fertilizer solutions.

Ammonium nitrate limestone Combination of ammonium nitrate (NH_4NO_3) and limestone forms a product containing 20.5% nitrogen.

Ammonium phosphate Product manufactured by reacting ammonia (NH_3) with phosphoric acid (H_3PO_4). Different phosphates can be formed, depending on the amount of NH_3 used. Two commonly used in fertilizers are monoammonium phosphate ($NH_4H_2PO_4$) (11-48-0) and diammonium phosphate [$(NH_4)_2HPO_4$] (21-53-0, 16-48-0, and 18-46-0). The last two products result when wet process H_3PO_4 is used.

Ammonium phosphate sulfate Wet process phosphoric acid (H_3PO_4) containing an excess of sulfuric acid (H_2SO_4) is neutralized with ammonia (NH_3) to make products such as 16-20-0.

Ammonium sulfate [$(NH_4)_2SO_4$] Solid material manufactured by reacting ammonia (NH_3) with sulfuric acid (H_2SO_4), typically containing 20.5 to 21% nitrogen.

Analysis The determination of composition by chemical means and expressed in terms that physical laws require or permit. Although *analysis* and *grade* sometimes are used synonymously, *grade* applies only to the three primary plant nutrient elements (N, available P_2O_5, and soluble K_2O) and is stated as the guaranteed minimum quantities present. See *grade*.

Anhydrous ammonia (NH_3) Gas containing approximately 82% nitrogen. Under pressure, ammonia gas is changed to a liquid and is stored and transported in this form.

Aqua ammonia (NH_4OH) Ammonium hydroxide formed by dissolving anhydrous ammonia (NH_3) in water. Commercial grades of NH_3 liquor usually contain 20 to 25% nitrogen. Most of it is used either for direct application to the soil or in the manufacture of ammoniated superphosphates.

Available phosphate The P_2O_5 equivalent of a water-soluble fertilizer with neutral ammonium citrate considered readily available to growing plants. (P_2O_5 is phosphorus pentoxide. P_2O_5 is not found in fertilizers, but has been historically accepted as expressing P content.) The traditional term, available phosphoric acid (H_3PO_4, frequently abbreviated as APA), is a misnomer because phosphoric acid is H_3PO_4.

Basic slag By-product of steel manufacture containing lime, phosphate (P_2O_5) and small amounts of other plant food elements such as S, Mn, and Fe. Basic slags may contain 10 to 17% P_2O_5, 35 to 50% Ca, and 2 to 10% MgO. The available P_2O_5 content of most American slag is in the range of 8 to 10%.

Blended fertilizer Mechanical mixture of different fertilizer materials.

Bone meal Raw bone meal consists of ground cooked bones from which no gelatin or glue has been removed. Steamed bone meal is cooked under pressure to dissolve some of the gelatin.

Borax ($Na_2B_4O_7·10H_2O$) Salt used in fertilizer as a source of B. Fertilizer borax contains about 11% B.

Brand Term, design, or trademark used in connection with one or several grades of fertilizer; trade name assigned by a manufacturer to its fertilizer product.

Brand name or product name Specific designation applied to a certain fertilizer.

Bulk-blended fertilizer Mixture of dry granular fertilizer materials to yield specific ratios and grades. Individual granules in a bulk-blended fertilizer do not have the same ratio and content of plant food as the total mixture.

Bulk fertilizer Commercial fertilizer delivered to the purchaser in an unpackaged solid or liquid state to which a label cannot be attached.

Calcite Limestone containing mostly $CaCO_3$; more commonly known as ground agricultural limestone. See *liming materials*.

Calcium ammonia nitrate Product formed by reacting $CaCO_3$ and NH_4NO_3; typically contains 27% N.

Calcium carbonate ($CaCO_3$) Principal component of calcitic limestone and one of the main components of dolomitic limestone ($MgCO_3$ is the other). Marl and oyster shells are composed primarily of $CaCO_3$. See *calcite* and *liming materials*.

Calcium cyanamide ($CaCN_2$) Organic material containing approximately 21% N; alkaline in reaction; is used as a fertilizer and as a defoliant to control weeds and certain soil-borne diseases.

Calcium oxide (CaO) Active ingredient in certain liming materials; liming materials are sometimes compared based on their calcium oxide equivalents. See *liming materials*.

Calcium phosphate Calcium phosphate has several forms; the most prevalent in nature is apatite, a highly insoluble form found mainly as phosphate rock. Apatite is changed into more soluble monocalcium phosphate monohydrate [$Ca(H_2PO_4)_2 \cdot H_2O$], and $CaSO_4$ in the manufacture of superphosphate. See *superphosphate.*

Calcium sulfate See *gypsum*.

Complete fertilizer Compound or blend of compounds used for its significant quantities of N, P, and K; may contain other plant nutrients.

Compound fertilizer Fertilizer formulated with two or more plant nutrients.

Concentrated superphosphate Also called triple superphosphate (TSP); manufactured by reacting H_3PO_4 with phosphate rock; product has a P_2O_5 equivalent of 44 to 48%, depending on the ratio of the acids used; contains only a minor amount of gypsum.

Controlled release fertilizer Term used interchangeably with *delayed release*, *slow release*, *controlled availability*, *slow acting*, and *metered release* to designate controlled dissolution of fertilizer at a lower rate than conventional water-soluble fertilizers. Controlled release properties may result from coatings on water-soluble fertilizers or from low dissolution and/or mineralization rates of fertilizer materials in soil.

Copper sulfate ($CuSO_4 \cdot 5H_2O$) Most common source of Cu for fertilizer; 25% Cu; also used as an insecticide and fungicide; common name is blue vitriol.

Diammonium phosphate See *ammonium phosphate.*

Dolomite Material used to lime soils in areas where Mg and Ca are needed; made by grinding dolomitic limestone which contains $MgCO_3$ and $CaCO_3$. See *liming materials.*

Ferrous sulfate ($FeSO_4 \cdot 7H_2O$) Green vitriol; used as a source of Fe, especially in alkaline soils.

Fertigation Application of plant nutrients in irrigation water to accomplish fertilization.

Fertilizer Organic or inorganic material of natural or synthetic origin (other than liming materials) added to soils to supply one or more elements essential to plant growth; any material or mixture that supplies plant nutrient elements.

Fertilizer analysis Percent composition of a fertilizer determined in a laboratory and expressed as total N, available phosphoric acid (P_2O_5), and water-soluble potash (K_2O).

Fertilizer grade Minimum guarantee of available plant nutrient expressed in terms of total N, available phosphate or phosphorus, and soluble potash or potassium. The numerals used to designate N, P_2O_5, and K_2O must coincide with the guaranteed analysis statement. Only one set of numerals may be used in a grade designation (a set of three numbers in sequence that express percents of total nitrogen, available phosphate and soluble potash). A 5-10-15 grade contains 5% N, 10% P_2O_5, and 15% K_2O. A missing nutrient is represented by a zero. For example, 46-0-0 designates urea; 0-46-0 is for triple superphosphate, 0-0-60 is for potassium chloride (muriate), and 18-46-0 is for diammonium phosphate. The analysis is usually designated as N-P_2O_5-K_2O, but it may be N-P-K where permitted or required under state law.

Fertilizer ratio Relative proportion of primary nutrients in a fertilizer grade divided by the highest common denominator for the grade, e.g., grades 10-6-4 and 20-12-8 have 5:3:2 ratios; the ratio of two or more nutrient percentages to another, e.g., 5-10-15 grade has a 1:2:3 ratio and 0-10-20 has a 0:1:2 ratio.

Fertilizer requirement The quantity of a certain plant nutrient needed to increase growth to a designated level in addition to the amount supplied by soil.

Filler Substance added to fertilizer to provide bulk, prevent caking, or serve a purpose other than providing essential plant nutrients.

Fluid fertilizer A fluid in which essentially all the plant nutrient elements are in solution; a fertilizer wholly or partially in solution that can be handled as a liquid, including clear liquids and liquids containing solids in suspension.

Foliar fertilization Application of a dilute solution of fertilizer nutrients to plant foliage to supplement nutrients absorbed by plant roots. See *nitrogen solutions*.

Formula Designation of quantities of various ingredients combined to make a fertilizer.

Grade Guaranteed analysis of a fertilizer containing one or more primary plant nutrient elements. Grades are stated as guaranteed percentages of total nitrogen (N), available phosphate (P_2O_5), and soluble potash (K_2O) in that order. For example, a 10-10-grade contains 10% total nitrogen (N), 10% available phosphate (P_2O_5), and 10% soluble potash (K_2O). See *analysis.*

Granular fertilizer Particular form of fertilizer. Particles are sized between upper and lower limits or between two screen sizes, usually within the range of 1 to 4 mm and often more closely sized. The desired size may be obtained by agglomerating smaller particles, crushing and screening larger particles, controlling size by crystallization processes, or prilling.

Guano Decomposed dried excrement of birds and bats. Most guano came from islands off the coast of Peru and was derived from the excrement of sea fowl. Guano is high in N and PO_4, and was once a major fertilizer in the U.S.

Gypsum ($CaSO_4{\cdot}2H_2O$) Common name for calcium sulfate, a mineral used in fertilizers as a source of Ca and S. Gypsum also is used widely in reclaiming alkali soils in the western U.S.; also known as landplaster. Pure form contains approximately 18.6% S.

Hygroscopic Material that tends to absorb moisture from the atmosphere. Many materials used for fertilizer are hygroscopic and may require special treatment to prevent caking.

Injected fertilizer Placement of fluid fertilizer or anhydrous ammonia into the soil via pressure or nonpressure systems.

Inorganic fertilizer Fertilizer material in which carbon is not an essential component of its basic chemical structure. Urea is often considered an inorganic fertilizer because of its rapid hydrolysis to form ammonium ions in soil.

Landplaster See *gypsum.*

Lime Calcium oxide (CaO); in agricultural usage, *lime* denotes any liming material. See *liming materials.*

Liming materials *Lime* and *liming materials* in common agricultural usage designate any material containing Ca, Mg, or both that can neutralize soil acidity. Common sources of liming materials are limestone (calcitic and dolomitic), marl, and oyster shells. The most common materials are ground calcitic limestone and ground dolomitic limestone, both simply referred to as *ground agricultural limestone*.

Liquid fertilizer A fluid in which the plant nutrients are in a true solution.

Magnesium carbonate ($MgCO_3$) Principal component of dolomitic limestone; $CaCO_3$ is the other.

Magnesium oxide (MgO) Active ingredient of certain liming materials that supply Mg and Ca to the soil.

Magnesium sulfate ($MgSO_4{\cdot}NH_2O$) Soluble salt used as a source of Mg; common forms are Epsom salts and the kieserite (9 to 18% Mg). See *liming materials* and *dolomite.*

Manganese sulfate ($MnSO_4{\cdot}H_2O$) Solid compound used as a source of Mn for plants; contains 26 to 28% Mn.

Micronutrient Seven nutrient elements required in very small quantities: B, Cl, Cu, Fe, Mn, Mo, and Zn, in addition to the primary nutrients that are essential for the normal growth of plants; may need to be added to growth media.

Mixed fertilizer Two or more fertilizer materials blended or granulated together into individual mixes. The term includes dry mix powders, granulated mixes, clear liquids, suspensions, and slurry mixtures.

Monoammonium phosphate See *ammonium phosphate.*

Muriate of potash (KCl) Principal source of fertilizer K; chemical name is potassium chloride; usually sold on the basis of a material containing 95 to 99% KCl with a K_2O equivalent of 60 to 62%.

Nitrate of soda ($NaNO_3$) Fertilizer material containing approximately 16% N; correct chemical name is sodium nitrate; principal sources were natural deposits in Chile; also produced synthetically.

Nitric phosphate Phosphate fertilizer made by reacting HNO_3 with phosphate rock. Usually another acid such as sulfuric or phosphoric acid is added.

Nitrification A process by which bacteria form nitrates from ammonium (NH_4) nitrogen.

Nitrogen solutions Water solutions of ammonia (NH_3), ammonium nitrate (NH_4NO_3), and sometimes urea [$CO(NH_2)_2$] and other soluble nitrogen compounds used in ammoniating superphosphate, the manufacture of complete fertilizer, and as a source of N for direct application to soil. These pressure and nonpressure solutions vary in composition and N content.

Normal superphosphate Compound manufactured by mixing H_2SO_4 and finely ground phosphate rock to produce a material composed mainly of monocalcium phosphate ($CaHPO_4$) and gypsum. Small amounts of unreacted rock and H_3PO_4 may also be present. Normal superphosphate has a P_2O_5 equivalent of 18 to 20%.

Organic fertilizer A material containing carbon and one or more plant nutrients in addition to hydrogen and/or oxygen. Urea is often considered an inorganic fertilizer because of its rapid hydrolysis to form ammonium ions in soil. Although some organic fertilizers are manufactured synthetically, the term generally applies to products derived from plant or animal materials, such as manure, sewage sludge, castor pomace, and process tankage.

pH Potential hydrogen; expresses a measurement of hydrogen ion (H^+) activity or concentration in a solution. The pH scale from 1 to 14 denotes the relative intensity of acidity or alkalinity. A neutral material has a pH of 7.0. Values below 7.0 denote progressively more intense acid conditions, and those above 7.0 more intense alkaline conditions.

Phosphoric acid (H_3PO_4) Inorganic acid used to manufacture concentrated superphosphate and ammonium phosphate; sometimes directly applied; produced from phosphate rock and H_2SO_4; three forms are filter grade unconcentrated acid, 30 to 32% P_2O_5; merchant grade concentrated acid, 54% P_2O_5; and superphosphoric concentrated acid, 65 to 72% P_2O_5.

Phosphoric anhydride See *available phosphate*.

Phosphoric oxide See *available phosphate*.

Phosphorus pentoxide See *available phosphate*.

Plant nutrient element Also called plant food or plant food element; material essential for plant growth.

Pop-up fertilizer Fertilizer placed in small amounts in direct contact with seeds.

Potash Potassium oxide (K_2O) equivalent; the K_2O form is never found in fertilizer, but historically has been used to express K content.

Potassium chloride (KCl) See muriate of potash.

Potassium nitrate (KNO_3) Solid material containing approximately 13% N and 44% K_2O.

Potassium sulfate (K_2SO_4) Solid material with a K_2O equivalent of 48 to 53%; also called sulfate of potash.

Primary nutrient element Nitrogen, phosphorus or phosphate, and potassium or potash; called primary or major elements because of the relatively large quantities needed for healthy plant growth; most common constituents of commercial fertilizers.

Ratio The numerical relationship of concentrations of the primary nutrient elements in a fertilizer, e.g., 5-10-15 grade has a 1:2:3 ratio of elements.

Salt index Index used to compare solubilities of chemical compounds. Most N and K_2O compounds have high indices; PO_4 compounds have low indices. When applied too close to seeds or on foliage, compounds with high indices can cause salt injuries.

Salt index fertilizer Ratio of the decrease in osmotic potential of a solution containing a fertilizer compound or mixture to that produced by the same weight of $NaNO_3 \times 100$.

Secondary nutrient Nutrient other than the primary elements essential to plant growth; may have to be added to growth medium. Secondary plant nutrients include Ca, Mg, and S; micronutrients include B, Cl, Co, Cu, Fe, Mn, Mo, Na, and Zn.

Side-dressed fertilizer Application of fertilizer to the sides of crop rows after plant emergence.

Slow-release fertilizer See *controlled release fertilizer.*

Slurry fertilizer Fluid mixture containing dissolved and undissolved plant nutrient materials; requires continuous mechanical agitation to assure uniform content.

Sodium nitrate ($NaNO_3$) See *nitrate of soda.*

Sodium molybdate ($Na_2MoO_4{\cdot}2H_2O$) Common source of Mo micronutrient.

Soluble potash K_2O equivalent of a fertilizer soluble in an aqueous solution of 0.8% ammonium oxalate after boiling in a 1.4% solution of ammonium oxalate.

Starter fertilizer Fertilizer applied in relatively small amounts with or near seed for the purpose of accelerating early plant growth.

Sulfate of ammonia See *ammonium sulfate.*

Sulfate of potash-magnesia ($2MgSO_4{\cdot}K_2SO_4$) Solid material, also called langbeinite, found in salt deposits primarily in New Mexico and in several European countries. The commercial product usually has a K_2O equivalent of about 21%, and contains 53% $MgSO_4$ and not more than 2.5% Cl; used in fertilizer as a source of K_2O and Mg.

Suspension Saturated solution in which some plant nutrient elements are suspended (by gelling clay) in a saturated solution. Anhydrous ammonia (NH_3) is the major source of agricultural N. It is a high-pressure liquid used in the manufacture of other fertilizers.

Suspension fertilizer Fluid fertilizer containing dissolved and undissolved plant nutrients. Undissolved nutrients are kept in suspension with a suspending agent, usually a swelling clay. The suspension must be flowable enough to be mixed, pumped, agitated, and applied to the soil in a homogeneous mixture. The suspension of the undissolved nutrients may be inherent to the materials or produced with a suspending agent that has nonfertilizer properties. Occasional mechanical agitation may be necessary to facilitate uniform suspension of undissolved nutrients.

Tankage Animal feed; process tankage is made from leather scrap, wool, and other inert nitrogenous materials by steaming under pressure with or without adding acid; also contains P.

Top-dressed fertilizer Surface application of fertilizer to a soil after the crop is established.

Triple superphosphate See *concentrated superphosphate*.

Unit A unit of plant nutrient element is 1% of a ton or 20 lb. A ton of a 6-12-12 fertilizer contains 6 units of N, 12 units of P_2O_5, and 12 units of K_2O.

Urea [$CO(NH_2)_2$] Solid synthetic organic material containing approximately 45% N; when applied to soil, its N changes first to the ammonium (NH_4) form, then to the nitrate (NO_3) form.

White vitriol or zinc sulfate ($ZnSO_4{\cdot}7H_2O$) Solid material used as a source of Zn for plants; contains 36% Zn.

TABLE 9.4
Molecular Weights of Essential Nutrient Elements, Compounds, and Ions

Essential Element	Form	Molecular Weight (g/mol)
Nitrogen	N	14.01
	NH_4^+	18.05
	NO_3^-	62.01
Phosphorus	P	30.97
	P_2O_5	141.94
Potassium	K	39.1
	K_2O	94.4
	KCl	74.5
Calcium	Ca	40.08
	CaO	56.08
	$CaSO_4$	136.14
Magnesium	Mg	24.31
	MgO	40.31
Sulfur	S	32.06
	SO_4^{2-}	96.06
	SO_2	64.1
Boron	B	10.81
	B_2O_3	69.6
	$Na_2B_4O_7{\cdot}5H_2O$	227.2
Copper	Cu	63.55
	$CuSO_4$	159.61
Iron	Fe	55.85
	$FeSO_4$	151.91
Manganese	Mn	54.94
	$MnSO_4$	151.0
Zinc	Zn	65.38
	ZnO	81.4
	$ZnSO_4{\cdot}H_2O$	179.5

9.4 MAJOR ELEMENTS OF FERTILIZERS

TABLE 9.5
Major Element-Containing Fertilizer Materials, Their Formulations, Forms, and Percent Contents

Nitrogen (N)

Source	Formula	Form	% N
Inorganic			
Ammonium nitrate	NH_4NO_3	Solid	34
Ammonium sulfate	$(NH_4)_2SO_4$	Solid	21
Ammonium thiosulfate	$(NH_4)_2SO_3$	Liquid	12
Anhydrous ammonia	NH_3	Gas	82
Aqua ammonia	NH_4OH	Liquid	2–25
Nitrogen solutions	Varies	Liquid	19–32
Monoammonium phosphate	$NH_4H_2PO_4$	Solid	11
Diammonium phosphate	$(NH_4)_2HPO_4$	Solid	1–18
Calcium cyanamide	$CaCN_2$	Solid	21
Calcium nitrate	$Ca(NO_3)_2$	Solid	16
Sodium nitrate	$NaNO_3$	Solid	16
Potassium nitrate	KNO_3	Solid	13
Synthetic organic			
Urea	$CO(NH_2)_2$	Solid	45–46
Sulfur-coated urea	$CO(NH_2)_2$-S	Solid	40
Urea-formaldehyde	$CO(NH_2)_2$-CH_2O	Solid	38
Natural organic			
Cotton seed meal		Solid	12–13
Milorganite		Solid	12
Animal manure		Solid	10–12
Sewage sludge		Solid	10–20
Chicken litter		Solid	20–40

Phosphorus (P)

		% Available P_2O_5	
Source	**Formula**	**Citrate Soluble**	**Water Soluble**
Superphosphate, 20% (0–20–0)	$Ca(H_2PO_4)_2$	16–22	90
Concentrated superphosphate (0–45–0)	$Ca(H_2PO_4)_2$	44–52	95–98
Monoammonium phosphate	$NH_4H_2PO_4$	48	100
Diammonium phosphate	$(NH_4)_2HPO_4$	46–48	100
Ammonium polyphosphate	$(NH_4)_3HP_2O_7 \cdot H_2O$	34	100
Phosphoric acid	H_3PO_4	55	100
Superphosphoric acid, polyphosphate	$H_3PO_4 + H_4P_2O_7$	76–85	100
Rock phosphate fluor- and chloroapatites	$3Ca_3(PO_4)_2 \cdot CaF_2$	3–26	0
Basic slag	$5CaO \cdot P_2O_5 \cdot SiO_2$	2–16	—
Bone meal		22–28	—

Potassium (K)

Compound	Formula	% K
Potassium chloride (muriate of potash)	KCl	60–63
Potassium sulfate	K_2SO_4	50–52
Potassium magnesium sulfate (SUL-PO-MAG)	$K_2SO_4{\cdot}MgSO_4$	22
Potassium nitrate	KNO_3	44
Potassium hydroxide	KOH	83

Calcium Liming and Fertilizer Sources [a]

Carrier	Formula	% Ca
Liming materials		
Blast furnace slag	$CaSiO_3$	29
Calcitic limestone	$CaCO_3$	32
Dolomitic limestone	$CaCO_3 + MgCO_3$	22
Hydrate lime	$Ca(OH)_2$	46
Precipitated lime	CaO	60
Fertilizers		
Calcium nitrate	$Ca(NO_3)_2$	19
Superphosphate, normal	$Ca(H_2PO_4)_2 + CaSO_4{\cdot}2H_2O$	20
Superphosphate, triple	$Ca(H_2PO_4)_2$	14
Others		
Gypsum	$CaSO_4{\cdot}2H_2O$	23
Gypsum (by-product)	$CaSO_4{\cdot}2H_2O$	17[b]
Gypsum (impure)	$CaSO_4{\cdot}2H_2O$	15[b]

[a] For acid soils, it is generally assumed that maintaining soil pH within the optimum range (5.8 to 7.5) by frequent liming will provide sufficient Ca to meet crop requirements.
[b] Ca content varies.

Magnesium (Mg)

Source	Formula	Water Solubility	% Mg
Dolomitic limstone	$CaCO_3 + MgCO_3$	Insoluble	6–12
Kieserite (magnesium sulfate)	$MgSO_4{\cdot}H_2O$	Slightly	18
Epsom salt (magnesium sulfate)	$MgSO_4{\cdot}2H_2O$	Soluble	10
Potassium magnesium sulfate	$K_2SO_4{\cdot}MgSO_4$	Soluble	11
Pro/Mesium	$3MgOSiO_2{\cdot}2H_2O$	Insoluble	22
Magnesium oxide	MgO	Slightly	50–55

Note: For acid soils and for Ca, it is generally assumed that maintaining soil pH within the optimum range (5.8 to 7.5) by frequent liming using dolomitic (Mg-bearing) limestone or other high-content Mg liming materials will provide sufficient Mg to meet crop requirements.

Sulfur (S)

Source	Formula	% S
Sulfur	S	90–100
Ammonium sulfate	$(NH_4)_2SO_4$	24
Gypsum	$CaSO_4{\cdot}2H_2O$	19
Magnesium sulfate (Epsom salt)	$MgSO_4{\cdot}7H_2O$	13
Potassium sulfate	K_2SO_4	18
Potassium magnesium sulfate (SUL-PO-MAG)	$K_2SO_4 + MgSO_4$	23
Superphosphate (0-20-0)	$CaSO_4$ + calcium phosphate	12
Ammonium thiosulfate	$(NH_4)_2S_2O_3$	26
Sulfur-coated urea	$CO(NH_2)_2$-S	10
Nitrogen-S solution	$CO(NH_2)_2{\cdot}NH_4NO_3{\cdot}(NH_4)_2SO_4$	2–5

TABLE 9.6
Common Fertilizers and Their Characteristics

Name	Fertilizer Ratio	Physical Properties	Comments
		Fertilizers used primarily as sources of nitrogen (N)	
Anhydrous ammonia	82-0-0	Compressed gas; high affinity for water; pungent odor; corrosive	Must be placed at 46 in. depth; hazardous; safety precautions and high pressure required
Urea[a]	46-0-0	Granular	Applied prior to or after seeding; much less corrosive than other nitrogen fertilizers; avoid mixing with ammonium nitrate as attraction for moisture causes mixture to turn to slush; more subject to volatilization losses than ammonium nitrate when not incorporated in soil; volatilization losses enhanced when urea is broadcast without incorporation under warm and windy conditions on alkaline, calcareous, or drying soils
Nitrogen solution (UAN)	28-0-0	Solution; 50% of nitrogen is in urea form and 50% is in ammonium nitrate form; contains 9.79 lb N/L or 357 lb N/Imp gal	Can be applied prior to or after seeding; may be injurious to crops when applied after emergence; can be applied with certain pesticides; urea portion is subject to volatilization losses when nitrogen solution is surface-applied and not incorporated; losses enhanced when solution is surface-applied without incorporation under warm and windy conditions on alkaline, calcareous, or dry soil.
Ammonium nitrate[a]	34-0-0	Granular; prilled	Larger amount than urea can be applied with seed of cereal crops; can be applied prior to or after seeding; avoid mixing with urea as attraction for moisture causes mixture to turn to slush; less subject to volatilization losses than urea when broadcast without incorporation.
		Fertilizers used primarily as sources of phosphorus (P)	
Monoammonium phosphate (MAP)	12-51-0; 11-52-0; 10-50-0	Solid, granular; fairly resistant to breakdown during handling	Most commonly used high analysis dry phosphorus fertilizers
Dammonium phosphate (DAP)	18-46-0	Solid, granular	Phosphorus availability to plants similar to monoammonium phosphate; more toxic than MAP when placed with seed
Ammonium polyphosphate	10-34-0	Liquid; contains 0.31 lb N and 1.06 lb P_2O_5/L or 1/42 lb N and 4.83 lb P_2O_5/Imp gal	Phosphorus availability to plants similar to MAP
Phosphoric acid	0-54-0	Liquid; contains 1.87 lb P_2O_5/L or 8.50 lb P_2O_5/Imp gal	Burns skin on contact; requires specialized delivery systems that can withstand corrosiveness of product; primarily used for dual band applications with N fertilizers
Triple superphosphate	0-45-0	Solid, granular	Phosphorus availability less than for phosphorus fertilizer containing ammonium

TABLE 9.6 (CONTINUED)
Common Fertilizers and Their Characteristics

Name	Fertilizer Ratio	Physical Properties	Comments
		Fertilizers used primarily as sources of potassium (K)	
Potassium chloride (potash)	0-0-60; 0-0-62	Crystalline; hydroscopic; soluble	Most commonly used potassium fertilizer in Manitoba; can be mixed with other fertilizers; contains chloride which is a nutrient and may help reduce incidence of some plant diseases
		Fertilizers used primarily as sources of sulfur (S)	
Ammonium sulfate	21-0-0-24; 20-0-0-24; 19-2-0-22	Crystalline; granular; granular	Applied prior to seeding; contains S in the readily available sulfate form; corrosive; highly acidifying; should not be used continuously or at high rates on acidic soils
Ammonium thiosulfate	12-0-0-26	Liquid; contains 0.35 lb N and 0.76 lb/S/L or 1.60 lb N and 3.46 lb S/Imp gal	Noncorrosive; contains S in readily available form
	15-0-0-20	Contains 0.43 lb N and 0.57 lb S/L or 1.96 lb N and 2.62 lb S/Imp gal	
Elemental sulfur	0-0-0-90	Can be blended with most dry fertilizers except ammonium nitrate	Must be oxidized to sulfate before plants can use it; apply one year before crop use
		Combination or blended fertilizers	
Ammonium nitrate; monoammonium phosphate[a]	23-22-0; 28-13-0	Solid; granular; a blend of 34-0-0 and 11-52-0	Suitable for nitrogen and phosphorus-deficient soils; phosphorus availability same as MAP
Urea; monoammonium phosphate[a]	27-27-0; 34-17-0, etc.	Solid; granular; blend of 46-0-0 and 11-52-0; fairly stable during storage and handling	Suitable for nitrogen- and phosphorus-deficient soils; nitrogen component can cause germination to seed at above-recommended rates
Monoammonium phosphate; ammonium sulfate	16-20-0-14; 17-20-0-15	Solid; granular; sources mixed into a common granule	Suitable for sulfur-deficient soils; phosphorus availability same as MAP; suitable size for blending

[a] Warning: Contact between urea (46-0-0) or urea blends and ammonium nitrate (34-0-0) or ammonium nitrate blends will cause the fertilizer to absorb moisture and turn into slush. Thoroughly clean all equipment and storage bins before switching from one product to another. Some micronutrient fertilizer may have similar compatibility problems with dry and liquid fertilizers, so consult manufacturer's instructions.

Note: When blending fertilizer, it is important to use fertilizer sources with evenly matched particle sizes. Using inconsistently sized sources will result in segregation of different fertilizers and may result in lost productivity and crop damage.

Source: *Soil Fertility Guide*, 1999, Manitoba Agriculture. (www.gov.mb.ca/agriculture/soilwater/soilfert/fbd02510.html)

TABLE 9.7
Properties of Major Element Fertilizer Materials

Material	N (%)	P_2O_5 (%)	K_2O (%)	Soil Reaction[a]	lb Lime/100 lb N[b]	Salt Index[c]
Ammonium nitrate	33.5	0	0	A	180	105
Monoammonium phosphate	11	48	0	A	180	30
Diammonium phosphate	18	46	0	A	180	3
Ammonium sulfate (23.7% S)	21	0	0	A	538	69
Ammonium polyphosphate	10	34	0	A	180	—
Urea	46	0	0	A	180	75
Liquid nitrogen	30	0	0	A	180	—
Calcium nitrate	15.5	0	0	N	0	65
Potassium nitrate	13	0	44	N	0	74
Muriate of potash	0	0	60	N	0	116
Potassium sulfate (18% S)	0	0	50	N	0	46
Sodium nitrate	16	0	0	B	0	100
Magnesium sulfate (10% Mg; 13% S)	0	0	0	N	0	44
Sulfate of potash-magnesia (11% Mg; 22% S)	0	0	22	N	0	43
Nitrate of soda-potash	15	0	14	N	0	19
Normal superphosphate (12% S)	0	20	0	N	0	10
Triple superphosphate	0	46	0	N	0	10
Gypsum (19% S; 22% Ca)	0	0	0	N	0	8

[a] A = acid; B = basic; N = neutral.
[b] Lb lime required to neutralize acid from 100 lb of nitrogen.
[c] Salt index for equal weights of materials, $NaNO_3$ = 100.

TABLE 9.8
Equivalent Weights of Common Fertilizers Supply Plant Nutrient Elements in Ionic Forms

Chemical Name	Formula	Ions Supplied	Equivalent Weight
Ammonium nitrate	HN_4NO_4	NH_4^+ and NO_3^-	80
Monoammonium phosphate	$NH_4H_2PO_4$	NH_4^+ and $H_2PO_4^-$	115
Diammonium phosphate (11-37-9)	$(NH_4)_2HPO_4$	NH_4^+ and HPO_4^{2-}	66
Ammonium sulfate	$(NH_4)_2SO_4$	NH_4^+ and SO_4^{2-}	66
Calcium nitrate	$Ca(NO_3)_2{\cdot}4H_2O$	Ca^{2+} and NO_3^-	118
Sodium nitrate	$NaNO_3$	Na^+ and NO_3^-	85
Phosphoric acid	H_3PO_4	H^+ and $H_2PO_4^-$	98 (usually 75, 80%)
Potassium chloride (muriate of potash)	KCl	K^+ and Cl^-	75
Potassium nitrate (saltpeter)	KNO_3	K^+ and NO_3^-	101
Potassium sulfate	K_2SO_4	K^+ and SO_4^{2-}	87
Magnesium sulfate (Epsom salt)	$MgSO_4{\cdot}7H_2O$	Mg^{2+} and SO_4^{2-}	123
Sulfuric acid	H_2SO_4	H^+ and SO_4^{2-}	58 (usually 85, 0%)
Nitric acid	HNO_3	H^+ and NO_3^-	65 (usually 85, 90%)

TABLE 9.9
Cold Water Solubility of Fertilizers

Fertilizer	Solubility (lb/100 gal)
Primary Materials	
Ammonium nitrate	984
Ammonium sulfate	592
Calcium nitrate	851
Diammonium phosphate	358
Magnesium sulfate	592
Monoammonium phosphate	192
Potassium nitrate	108
Sodium nitrate	608
Supersphosphate, ordinary	17
Supersphosphate, triple	33
Urea	651
Micronutrients	
Ammonium molybdate	Decomposes
Borax	8
Calcium chloride	500
Coppic oxide	Insoluble
Copper sulfate	183
Ferrous sulfate	242
Manganese sulfate	876
Sodium molybdate	467
Solubor	79 @ 68°F
Zinc sulfate	625

Source: *Knott's Handbook for Vegetable Growers*, 4th ed., 1997, John Wiley & Sons, New York.

TABLE 9.10
Equivalent Acidities of Major Commercial Fertilizers

	Equivalent Acidity	
Fertilizer	per 1,000 kg	per 2,000 lb
Ammonium nitrate, NH_4NO_3	593	1,188
Ammonium phosphate, $NH_4H_2PO_4$	724	1,450
Ammonium sulfate, $(NH_4)_2SO_4$	1,099	2,200
Anhydrous ammonia, NH_3	70	140
Nitrate of soda, $NaNO_3$	–292	–583
Urea, $CO(NH_2)_2$	749	1,500

TABLE 9.11
Parts per Million and Millequivalents per Liter Supplied When 1 lb or 1 kg of Material is Dissolved in 1,000 Gallons or 10 m³ of Water

Compound	Analysis[a]	lb/1,000 gal	ppm	kg/10 m³	lb/1,000 gal	meq/L[b]	kg/10 m³
NH_4NO_3	33.5-0-0	40	N	34	1.5	NH_4^+	1.3
					1.5	NO_3^-	1.3
NH_4Cl	25-0-0	30	N	25	2.2	NH_4^+	1.9
		79	C1	166	2.2	Cl^-	1.9
$(NH_4)_2SO_4$	20-0-0	24	N	20	1.8	NH_4^+	1.5
		29	S	24	1.8	SO_4^{2-}	1.5
$Ca(NO_3)_2{\cdot}4H_2O$	15-0-0	18	N	15	1.0	NO_3^-	0.8
		44	Ca	37	1.0	Ca^{2+}	0.8
$NaNO_3$	16-0-0	19	N	16	1.4	NO_3^-	1.2
		32	Na	27	1.4	Na^+	1.2
H_3PO_4	0-80-0[c]	80	P	64	1.2	$H_2PO_4^-$	1.0
KNO_3	13-0-44	16	N	13	1.2	K^+	1.0
		53	K_2O	53	1.2	NO_3^-	1.0
KCl	0-0-62	74	K_2O	62	1.6	K^+	1.3
		57	Cl	48	1.6	Cl^-	1.3
$(NH_4)_2HPO_4$	21-53-0	25	N	21	1.8	NH_4^+	1.5
		63	P_2O_5	53	1.8	HPO_4^{2-}	1.5
K_2SO_4	0-0-53	63	K_2O	53	1.4	K^+	1.1
		21	S	18	1.4	SO_4^{2-}	1.1
$NH_4H_2PO_4$	11-18-0	13	N	11	1.0	NH_4^+	0.9
		57	P_2O_5	48	1.0	$H_2PO_4^-$	0.9
$MgSO_4$	-	24	Mg	20	2.0	Mg^{2+}	1.7
		32	S	27	2.0	SO_4^{2-}	1.7
$Mg(NO_3)_2{\cdot}6H_2O$	11-0-0	13	N	11	0.9	Mg^{2+}	1.8
		11	Mg	10	0.9	NO_3^-	0.8
HNO_3 (pure)	18-0-0	21	N	18	1.9	NO_3^-	1.6
K_2HPO_4	0-11-54	49	P_2O_5	41	1.4	K^+	1.1
		64	K_2O	54	1.4	HPO_4^{2-}	1.1
KH_2PO_4	0-53-34	61	P_2O_5	53	1.0	K^+	0.8
		41	K_2O	34	1.0	$H_2PO_4^-$	0.8

[a] Analyses in percentage N, P_2O_5, and K_2O.
[b] Millequivalents calculated on the basis of equivalent weight.
[c] Percentage of H_3PO_4 in liquid.

TABLE 9.12
Conversion Factors for Nutrient Concentrations in Fertilizers

From	Multiply by	to get/from	Multiply by	to get
NO_3	0.226	N	4.426	NO_3
NH_3	0.823	N	1.216	NH_3
NH_4	0.777	N	1.288	NH_4
$CO(NH_2)_2$ -urea	0.467	N	2.143	$CO(NH_2)_2$ -urea
$(NH_4)_2SO_4$	0.212	N	4.716	$(NH_4)_2SO_4$
$NH_4\,NO_3$	0.350	N	2.857	$NH_4\,NO_3$
P_2O_5	0.436	P	2.292	P_2O_5
$Ca_3(PO_4)_2$	0.458	P_2O_5	2.185	$Ca_3(PO_4)_2$
K_2O	0.830	K	1.205	K_2O
KCl	0.632	K_2O	1.583	KCl
KCl	0.524	K	1.907	KCl
$ZnSO_4{\cdot}H_2O$	0.364	Zn	2.745	$ZnSO_4{\cdot}H_2O$
$ZnSO_4{\cdot}7H_2O$	0.227	Zn	4.398	$ZnSO_4{\cdot}7H_2O$
SO_2	0.500	S	1.998	SO_2
SO_4	0.334	S	2.996	SO_4
$MgSO_4$	0.266	S	3.754	$MgSO_4$
$MgSO_4{\cdot}H_2O$	0.232	S	4.316	$MgSO_4{\cdot}H_2O$
$MgSO_4{\cdot}H_2O$	0.130	S	7.688	$MgSO_4{\cdot}7H_2O$
$(NH_4)_2SO_4$	0.243	S	4.121	$(NH_4)_2SO_4$
SiO_2	0.468	Si	2.139	SiO_2
$CaSiO_3$	0.242	Si	4.135	$CaSiO_3$
$MgSiO_4$	0.280	Si	3.574	$MgSiO_3$
MgO	0.603	Mg	1.658	MgO
MgO	2.987	$MgSO_4$	0.335	MgO
MgO	3.434	$MgSO_4{\cdot}H_2O$	0.291	MgO
MgO	6.116	$MgSO_4{\cdot}7H_2O$	0.164	MgO
MgO	2.092	$MgCO_3$	0.478	MgO
CaO	0.715	Ca	1.399	CaO
$CaCO_3$	0.560	CaO	1.785	$CaCO_3$
CaO	0.715	Ca	1.399	CaO
$CaCl_2$	0.358	Ca	2.794	$CaCl_2$
$CaSO_4$	0.294	Ca	3.397	$CaSO_4$
$Ca_4(PO_4)_2$	0.388	Ca	2.580	$Ca_4(PO_4)_2$
$FeSO_4$	0.368	Fe	2.720	$FeSO_4$
$MnSO_4$	0.364	Mn	2.748	$MnSO_4$
MnCl	0.437	Mn	2.290	MnCl
$MnCO_3$	0.478	Mn	2.092	$MnCO_3$
MnO	0.632	Mn	1.582	MnO
$CuSO_4{\cdot}H_2O$	0.358	Cu	2.795	$CuSO_4{\cdot}H_2O$
$CuSO_4{\cdot}5H_2O$	0.255	Cu	3.939	$CuSO_4{\cdot}5H_2O$
$Na_2B_4O_7{\cdot}5H_2O$	0.138	B	7.246	$Na_2B_4O_7{\cdot}5H_2O$
$Na_2B_4O_7{\cdot}7H_2O$	0.123	B	8.130	$Na_2B_4O_7{\cdot}7H_2O$

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA.

TABLE 9.13
Physical Characteristics of Liquid Fertilizers

Grade	Weight	
	gal/lb	gal/ton
8-25-3	11.11	198.4
6-18-6	10.69	206.2
3-11-11	10.45	211.0
9-9-9	10.49	210.2
7-7-7	10.41	211.8
6-24-6	11.07	199.2
9-18-9	11.07	206.0
5-10-5	10.7	206.0
2-10-15	10.62	207.6
10-34-0	11.5	189.2
20-0-0 (28%)	10.65	207.0
20-0-0 (aqua ammonia)	7.49	294.3
54% phosphoric acid	13.15	167.7

TABLE 9.14
Granular Fertilizer Properties

Fertilizer	Grade	Salt Index	$CaCO_3$ Equivalent	Bulk (lb/ft^3)	Density (kg/L)
Urea	46-0-0	74.4	166	50	0.80
Ammonium nitrate	34-0-0	104	120	56	0.90
Calcium ammonium nitrate	27-0-0	93	55	68	1.10
Ammonium sulfate	21-0-0	68.3	151	68	1.10
Calcium nitrate	15.2-0-0	65	20 B	75	1.20
Potassium nitrate	14-0-41	69.5	26 B	75	1.20
Sodium nitrate	16.5-0-0	100	29 B	78	1.25
Superphosphate	0-20-0	7.8	Neutral	68	1.10
Triple superphosphate	0-46-0	10.1	Neutral	68	1.10
Monoammonium phosphate	11-52-0	26.7	95	62	1.00
Diammonium phosphate	18-46-0	29.2	102	62	1.00
Muriate of potash (red)	0-0-60	115	Neutral	70	1.10
Muriate of potash (white)	0-0-62	116	Neutral	75	1.20
Potassium sulfate	0-0-50	42.6	Neutral	75	1.20
Sulfate of potash-magnesium	0-0-22	43.4	Neutral	94	1.50

Notes: Grade: total nitrogen (N), phosphate (P_2O_5), and potash (K_2O). Salt Index: comparison of relative solubilities of fertilizer to sodium nitrate (100). $CaCO_3$ Equivalent: kg lime required to neutralize acidity in 100 kg fertilizer. B: Alkaline (acid neutralizing) material. Bulk Density: lb/ft^3 or kg/L — important when fertilizer is metered by volume rather than weight.

9.5 PHOSPHORUS FERTILIZERS[3]

Some important phosphate fertilizers and the reagents in which their solubilities are normally measured are:

Single (or normal) superphosphate — made by reacting phosphate rock with sulfuric acid. Water-soluble monocalcium phosphate is the active ingredient. The accompanying calcium sulfate (gypsum) co-product is a useful source of S. Solubility is determined by the proportion of neutral ammonium citrate that is soluble in water.

Triple superphosphate — made by reacting phosphate rock with phosphoric acid. Water-soluble monocalcium phosphate is the principal ingredient. Solubility is similar to that of single superphosphate.

Monoammonium and diammonium phosphates — made by reacting phosphoric acid with ammonia to produce water-soluble products; solubility is similar to that of superphosphates.

Nitrophosphates — range of products produced by reacting phosphate rock with nitric acid to produce a mixture of water-soluble monocalcium phosphate and calcium nitrate. The latter takes up water and must be removed. The the range of water solubilities depends on the amount of monocalcium phosphate converted to dicalcium phosphate.

Finely ground phosphate rock — cam be used only on acidic soils in which acidity slowly releases plant-available P. These finely ground materials are difficult to handle. In the humid tropics they have proven beneficial on plantation crops grown on acid soils. The more suitable phosphate rocks are classified as reactive. Their chemical composition allows rapid dissolution in the soil.

Compound fertilizers — monoammonium and diammonium phosphates are examples of fertilizers containing two plant nutrient elements. Fertilizers containing two or more nutrient elements contained in a single granule are called compound fertilizers. Manufacturers often produce a range of such fertilizers containing various proportions of N, P, and K.

Blended fertilizers — single or multinutrient element fertilizers that have granules or crystals about the same size and weight that can be blended to yield an almost infinite range of ratios of N, P, and K. The physical characteristics of the individual components are important to prevent separation during transport, handling, and spreading.

9.5.1 Availability of Different Forms of Soil Phosphorus

It is helpful to visualize the P cycle of the plant–soil system as a series of pools as shown in Figure 9.2. Water-soluble phosphorus added as fertilizers or manures goes first into the soil solution. From there, P is taken up by the plant roots or remains readily available or less readily available as a result of the reactions described in the figure.

Readily available P can be estimated by different soil analysis methods, but no single universal method exists for determining available P. Although the quantity of P extracted will vary with method, soils can be classified descriptively (e.g., deficient, sufficient, etc.) by using the analytical data obtained. The soil analysis methods most widely used gained acceptance because they adequately distinguished soils on the basis of the responsiveness of crops to applications of phosphate fertilizer.

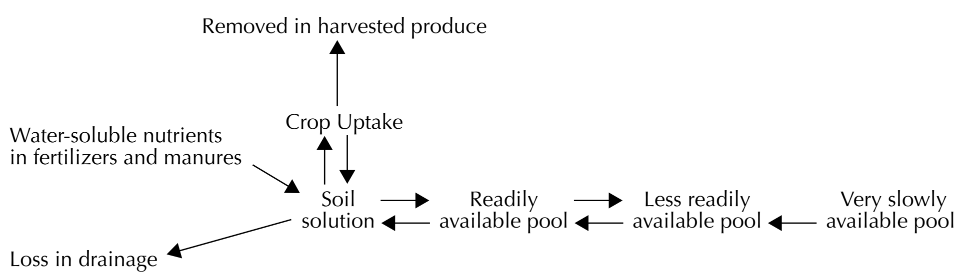


FIGURE 9.2 The phosphorus cycle in the plant–soil system. (*Source*: *Soil and Plant Phosphate*, 2000, International Fertilizer Industry Association, Paris.)

No routine soil analysis method is available to determine less readily available P. We know that the rates and amounts of P released from the pool can vary greatly. The results of P fractionation studies support an important feature shown in Figure 9.2, namely the reversible transfer of P between amounts in the soil solution and amounts in the readily and less available P pools. This seems to apply to many soils, although it may not apply to soils that have considerable capacities to fix P. Soil P reserves are not held in any particular soil P fraction.[3]

9.5.2 Effect of Soil Organic Matter on Phosphorus Availability

Soil organic matter (humus) plays an important role in P crop availability, which is not related to the mineralization of organic P. Humus apparently provides sites with low bonding energies for P, including P applied in fertilizers. Organic P in soils can be associated either with soil organic matter (humus) or P added recently as organic debris coming from plants or animals. Before this organic P can be recycled and used by plants, it must be mineralized by soil microbes and released into the soil solution as inorganic phosphate ions. The ions are then either taken up by plant roots or they enter into the same reactions with soil particles as added fertilizer phosphate ions and are distributed among the varous soil pools as shown in Figure 9.2.

9.5.3 Phosphorus for Winter Wheat

Findings of a multiyear study of a continuous wheat system in the Great Plains indicates that a single P fertilization can influence grain yields for several years. That means the cost of P fertilizer applications can be amortized over several years. The results show that a balanced N and P fertilization program is needed to optimize yields and economic returns and reduce the potential for nitrate-N contamination of ground water.[4]

9.6 FERTILIZER SOURCES — MICRONUTRIENTS

TABLE 9.15
Micronutrient-Containing Fertilizer Materials

Fertilizer Material	Formula	Water Solubility	Element Content (%)
	Boron (B)		
Boric acid	H_3BO_3	Soluble	17
	$Na_2B_4O_7{\cdot}5H_2O$	Soluble	20
	$Na_2B_4O_7{\cdot}10H_2O$	Soluble	11
	$Ca_2B_6O_{11}{\cdot}5H_2O$	Slightly soluble	10
Fertilizer Borate, 48	$Na_2B_4O_7{\cdot}10H_2O$	Soluble	14–15
Fertilizer Borate, granular	$Na_2B_4O_7{\cdot}10H_2O$	Soluble	14
Foliarel	$Na_2B_8O_{13}{\cdot}4H_2O$	Soluble	21
Solubor	$Na_2B_4O_7{\cdot}4H_2O + Na_2B_{10}O_{16}{\cdot}10H_2O$	Soluble	20
Borax	$Na_2B_4O_7{\cdot}10H_2O$	Soluble	11
	Chloride (Cl)		
Calcium chloride	$CaCl_2$	Soluble	50
Potassium chloride	KCl	Soluble	48
	Copper (Cu)[a]		
Copper sulfate (monohydrate)	$CuSO_4{\cdot}H_2O$	Soluble	35
Copper sulfate (pentahydrate)	$CuSO_4{\cdot}5H_2O$	Soluble	25
Cupric oxide	CuO	Insoluble	75
Cuprous oxide	Cu_2O	Insoluble	89

TABLE 9.15 (CONTINUED) Micronutrient-Containing Fertilizer Materials

Fertilizer Material	Formula	Water Solubility	Element Content (%)
Cupric ammonium phosphate	$Cu(NH_4)PO_4 \cdot H_2O$	Soluble	32
Basic copper sulfates	$CuSO_4 \cdot 3Cu(OH)_2$ (general formula)	Soluble	13–53
Cupric chloride	$CuCl_2$	Soluble	17
Copper chelates	$Na_2CuEDTA$	Soluble	13
	NaCuHEDTA	Soluble	9
Copper polyflavonoids	Organically bound Cu	Partially soluble	5–7
	Iron (Fe)[b]		
Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	Soluble	20
Ferric sulfate	$Fe(SO_4)_3 \cdot 4H_2O$	Soluble	23
Ferrous ammonium phosphate	$Fe(NH_4)PO_4 \cdot H_2O$	Soluble	29
Ferrous ammonium sulfate	$(NH_4)_2SO_4 \cdot FeSO_4 \cdot 6H_2O$	Soluble	14
Iron chelates	NaFeEDTA	Soluble	5–11
	NaFeHFDTA	Soluble	5–9
	NaFeEDDHA	Soluble	6
	NaFeDTPA	Soluble	10
	FeHEDTA	Soluble	5–9
	FeEDDHA	Soluble	6
Iron polyflavonoids	Organically bound Fe		9–10
	Manganese (Mn)[c]		
Manganese sulfate	$MnSO_4 \cdot 4H_2O$	Soluble	24
Manganese oxide	MnO	Insoluble	53
Manganese oxysulfate		Variable	30–50
Manganese chelate	MnEDTA	Soluble	5–12
	Molybdenum (Mo)[d]		
Sodium molybdate	$Na_2MoO_4 \cdot 2H_2O$	Soluble	39
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}$	Soluble	53
Molybdenum trioxide	MoO_3	Soluble	66
Molybdenum dioxide	MoO_2	Soluble	75
	Zinc (Zn)[e]		
Zinc sulfate	$ZnSO_4 \cdot 2H_2O$	Soluble	36
	$ZnSO_4$-NH_3 complex	Soluble	10–15
Zinc oxide	ZnO	Insoluble	60–78
Zinc oxysulfate		Variable	18–50
Zinc chelate	ZnEDTA	Soluble	6–14
Zinc oxide	ZnO		78–80
Zinc chelates	$Na_2ZnEDTA$		14
	NaZnTA		13
	NaZnHEDTA		9
Zinc Polyflavonoids	Organically bound Zn		10

[a] Copper can be applied to soil or foliage; some Cu sources are shown in this table.

[b] Iron sources can be applied to soil or foliage. Foliar application with a solution of ferrous sulfate ($FeSO_4$) or one of the chelated (EDTA or EDDHA) forms of Fe is most efficient.

[c] Manganese is best applied as a foliar spray to correct a deficiency; soil application can be inefficient due to inactivation of applied Mn. Row application of a P fertilizer increases Mn availability and uptake.

[d] Molybdenum is best supplied by seed treatment.

[e] Zinc can be applied as both soil and foliar applications.

TABLE 9.16
Synthetic Micronutrient Chelates

Chelating Agent	Micronutrient Content (%)			
	Copper	Iron	Manganese	Zinc
EDTA	7–13	5–14	5–12	6–14
HEEDTA	4–9	5–9	5–9	9
NTA	—	8	—	13
DTPA	—	10	—	—
EDDHA	—	6	—	—

Source: Western Fertilizer Handbook, Horticulture Edition, 1990, Interstate Publishers, Danville, IL. With permission from California Plant Health Association.

TABLE 9.17
Typical Application Rates of Micronutrient Fertilizers

Forms and Application Rates

Boron

Borax (10.6% B) is the most common fertilizer.
Soil application: 0.5 to 2.5 lb B/acre; 0.5 to 1 lb for most crops; higher rates for heavy feeders, such as alfalfa, beets, turnips.
Foliar spray: perennials — 0.2 lb B/100 gal water 1 to 3 wk after petal fall.
Annuals — several sprayings, e.g., 0.1 lb B/100 gal water weekly for 8 wk.

Copper

Copper sulfate (25 to 35% Cu) and copper oxide (75% Cu) are most common fertilizers.
Soil application: 2 to 6 lb Cu/acre; double that amount or more for muck soils.
Foliar spray: 0.8 lb Cu/100 gal water.

Iron

Ferrous sulfate (19% Fe) is the usual inorganic fertilizer; NaFeEDDH (6% Fe) and NaFeEDTA (5 to 14% Fe) are the best chelated forms.
Foliar spray: 3% solution of ferrous sulfate, possibly including a wetting agent, at a rate of 120 to 180 gal/acre starting when deficiency symptoms begin and continued at 2-wk intervals until they disappear.

Manganese

Manganous sulfate (26 to 28% Mn) and MnEDTA (12% Mn) are common.
Soil application: 5 to 10 lb inorganic Mn/acre, banded; broadcast application is much less effective.
Foliar spray: 0.5 to 1 lb Mn/100 gal water (inorganic or chelated) repeated 2 or 3 times.

Molybdenum

Ammonium or sodium molybdate are the usual fertilizers.
Seed treatment is the most common remedy, other than liming: 0.25 to 0.5 lb Mo/acre.
Soil application: 0.02 to 0.4 lb Mo/acre.

Zinc

Zinc sulfate (23 to 35% Zn) is a typical fertilizer.
Soil application is the usual treatment: 2 to 20 lb Zn/acre.
Foliar spray: 0.125 to 2.2 lb Zn/100 gal water, sprayed regularly until deficiency symptoms disappear.

TABLE 9.18
Relative Sensitivities of Selected Crops to Micronutrient Deficiencies

	Micronutrient				
Crop	**Boron**	**Copper**	**Iron**	**Manganese**	**Zinc**
Alfalfa	High	High	Medium	Medium	Low
Barley	Low	Medium	High	Medium	Medium
Clover	Medium	Medium	—[a]	Medium	Medium
Corn	Low	Medium	—	Medium	High
Oat	Low	High	Medium	High	Low
Rye	Low	Low	—	Low	Low
Sorghum	Low	Medium	High	High	High
Soybean	Low	Low	High	High	Medium
Sudan grass	Low	High	High	High	Medium
Sugar beet	High	Medium	High	Medium	Medium
Wheat	Low	High	Low	High	Low

[a] Inadequate data to categorize into low, medium, or high sensitivity groups.

TABLE 9.19
Soil Conditions and Crops Most Frequently Affected with Micronutrient Deficiencies

Micronutrient	Sensitive Crops	Soil Conditions for Deficiency
Boron	Alfalfa, clover, cotton, peanut, sugar beet, cereals	Acid sandy soils low in organic matter; overlimed soils; organic soils
Copper	Corn, small grains (oats), legumes	Organic soils; mineral soils high in pH and organic matter
Iron	Clover, sorghum, soybeans, rice	Leached sandy soils low in organic matter; alkaline soils; soils high in P
Manganese	Alfalfa, small grains (oats), soybeans, sugar beets	Leached acid soils; neutral to alkaline soils high in organic matter
Zinc	Corn, sorghum, legumes, grasses, soybeans	Leached acid sandy soils low in organic matter; neutral to alkaline soils; soils high in P

TABLE 9.20
Agronomic Crop Species Sensitive to Excessive Levels of Micronutrients

Micronutrient	Crop Species
Boron	Cereals
Chlorine	Cereals
Copper	Cereals, legumes
Iron	Rice
Manganese	Cereals, legumes
Zinc	Cereals

TABLE 9.21
Functions of Micronutrients

Micronutrient	Function
Boron	Regulates cell division
	Stimulates flowering and pollen production
	Increases fertility and improves fruit set
	Improves sugar concentration in reserve organs (sugar beets)
	Improves fixation of N in leguminous plants
	Essential to formation of healthy cell walls
Copper	Stimulates germination and growth
	Very important for fertility; deficiency causes sterile ears empty ears or half empty ears
	Reduces aging
	Improves resistance to flattening of cereals
Iron	Stimulates chlorophyll function
	With magnesium is essential for chlorophyll production
	Important for energy production and transport
	Stimulates protein synthesis and respiration
Manganese	Increases photosynthesis
	Increases resistance to frost (corn)
	Improves transformation of nitrites to amino acids and proteins
	Increases sugar content
Molybdenum	Essential for N fixation in leguminous plants
	Reduces nitrate (NO_3) accumulation
	Very important for transformation of N to proteins
	Increases protein content
Zinc	Essential in early stages of growth and fruit development
	Stimulates production of natural growth hormone (auxinen)
	Influences protein synthesis

TABLE 9.22
Most Common Micronutrient Deficiency Symptoms and Causes

Boron (average export: 60 to 300 g/ha)

Symptoms
Slowing of growth
Uncontrolled cell division between xylem and phloem
Brown spots that quickly become necrotic
Sugarbeet: heart rot and brown heart
Leguminous crops: yellowing of youngest leaves

Causes
Boron content depends on mineral composition of soil
Boron is strongly fixed on the clay–humus complex
The organic compound also fixes B and lowers availability
Increasing pH reduces B absorption capacity
Boron is easily leached by heavy rainfall
Deficiency symptoms occur when soils have high content of organic material, soils have high pH, after excessive liming, and during very dry periods

Copper (average export: 25 to 100 g/ha)

Symptoms
Monocotyls (cereals and corns) are much more sensitive then dicotyls
White flag syndrome appearing on tops of youngest leaves is typical of cereals; ripening of cereals is also delayed
Corn: nanism, shorter internodes, deformed and partially filled ears
Youngest leaves remain connected

Causes
Deficiency usually primary; certain soil types contain too little Cu, i.e., granite, basalt, and volcanic soils
Copper likely to be blocked in lightly acid soils with high organic content (plowed pastures, peaty soils)
Blockage in alkaline soils
Fresh organic matter makes Cu more available
Increasing pH lowers availability.
N and/or K excess blocks Cu and reduces availability

Iron (average export: 0.5 to 1.0 kg/ha)

Symptoms
Chlorosis; leaves turn yellowish-green to yellow; nerves remain green
Borders of leaves become necrotic in severe deficiency
Chlorosis always begins on youngest leaves

Causes
Soils with high content of active Ca
High pH (transformation to nonsoluble form)
Excessive liming
Too much phosphoric acid in soil
Excess of Cu, Zn, or Mn

Manganese (average export: 150 to 600 g/ha)

Symptoms
Diffuse chlorosis between nerves and borders of leaves; symptoms first appear on older leaves

continued

TABLE 9.22 (CONTINUED)
Most Common Micronutrient Deficiency Symptoms and Causes

Yellow clouds on older leaves of dicotyls (e.g., sugarbeets)

Causes

Availability of Mn is strongly linked to acidity of soil (more so than B, Zn, and Cu)
Deficiencies of Mn are more frequent when soil is poor in organic matter and pH is high; if soil is light (sandy) and has coarse structure
Deficiency also appears on soil with high level of active Ca
Excessive liming
In soils rich in organic matter, Mn^{2+} is transformed to an insoluble organic compound
An excess of Cu and/or Zn increases the chance of Mn deficiency

Molybdenum (average export: 10 to 20 g/ha)

Symptoms

Leguminous plants: poor development of nodules on roots, which causes low N fixation and absorption
Symptoms resemble those of N deficiency

Causes

Availability increases with high pH
Relatively large amounts of Mo are linked to organic materials
Deficiency appears mainly on acid soils, but also on neutral or alkaline soils from which Mo has been leached

Zinc (average export: 100 to 300 g/ha)

Symptoms

Slight symptoms: chlorosis on youngest leaves makes them almost white
Leaves stay small and pointed
Short internodes (rosetting)
Corn: 2 white strips on bottom parts of the oldest leaves and both sides of the mid-ribs; yellow to white color on youngest leaves
Squatted, stunted appearance due to poor juvenile growth

Causes

Raising pH reduces quantity of absorbable Zn
Occurs essentially in alkaline soils with high levels of organic matter
Antagonism with P
Badly structured soils produce poor rooting
Cold and humid spring weather

9.7 FERTILIZER PLACEMENT AND RATES

9.7.1 Fertilizer Placement

Placing fertilizer in the proper part of the root zone ranks in importance with applying the correct amounts of plant nutrient elements, according to experts with the Potash and Phosphate Institute. Researchers identified four basic objectives in fertilizer placement:

- To achieve efficient use of nutrient elements from plant emergence to maturity
- To prevent or reduce harmful effects to the environment
- To avoid fertilizer-induced salt injuries to plants
- To provide convenient and economical operations for custom applicators and their farmer customers

This section describes various application procedures according to location in the soil and method of placement. With the exception of foliar fertilization, fertilizers are normally applied to the soil surface or beneath the surface at varying depths. Many of the new techniques involve placement below the soil surface. The descriptions of the different methods of fertilizer placement may help applicators understand the various options available to them as the farmer customers strive for more economical crop production.

9.7.1.1 Banding

Banding is a general term implying methods that concentrate fertilizers into narrow zones that are kept intact to provide concentrated sources of nutrient elements. Applications may be made prior to, during, or after planting. Banding is particularly effective where soil nutrient element levels are low, where soils tend to readily revert applied nutrient elements into unavailable forms (fixation), where early season stress from cool or wet conditions limits root growth, where compaction limits root development, and where large amounts of surface residue limit soil–fertilizer contact.

Generally, banding of P, K, and micronutrients results in better utilization of applied nutrient elements during the first cropping season and better N application for reduced tillage systems where first-year responses are essential.

9.7.1.2 Surface Strip or Dribble Banding

Strip banding or dribbling is a placement form involving application of solid or fluid fertilizers in bands or strips of varying widths on the soil surface or on the surfaces of crop residues. Zones of high nutrient element concentration that improve nutrient use are produced. Typically, the fertilizer material contacts 25 to 30% of the soil surface. If surface strip applications are followed by tillage, the concentration effect is diluted to something between broadcast applications and subsurface banding where the concentrated zones remain intact.

9.7.1.3 Deep Banding

Deep banding is preplant application of nutrient elements 2 to 6 in. below the soil surface. Some applications may be as deep as 15 in. The applied nutrient elements may be in solid, fluid, or gaseous form. Concentrated zones of nutrient elements are produced — streams, sheets, or points, depending on the design of the applicator. In some areas, this fertilization is applied many months before the next crop is seeded, often in conjunction with a tillage operation.

In some areas of the southern U.S. coastal plains, deep banding with a shank running immediately ahead and below the planting unit is common. Large amounts of nutrient elements are placed immediately below the seed, and compacted zones are opened to root development.

Dual application, another term for deep banding, implies simultaneous application of anhydrous ammonia as the main N source with fluid or solid P, K, and S fertilizers. Otherwise, deep banding terminology can imply the use of either fluid or solid fertilizers.

9.7.1.4 High Pressure Injection

This method of deep banding application of liquid fertilizer employs high pressure to force a constant stream or pulse of fertilizer through surface residue and into the soil. No physical disturbance of the soil is necessary. Pressures range from 2,000 to 6,000 psi. Advantages for this method of application are the same as for deep banding, but the depth of penetration is less.

9.7.1.5 Point Injection of Fluids

This technique of liquid fertilizer application is another variation of deep placement that employs a spoked wheel to inject nutrient elements at points about 8 in. apart to a soil depth of 4 to 5 in. Spacings between the wheels can be varied according to crop to be fertilized. A rotary valve in the wheel hub dispenses fertilizer to the "down" spike from a positive displacement pump.

9.7.1.6 Point Placement of Solids

Deep placed "nests", "pockets", "chutkis", or super granules of solid fertilizers are in developmental stages. This technique was conceived primarily to concentrate ammoniacal sources of N in localized zones at approximately the same soil depths as regular deep banding. Solid sources of conventionally sized urea or ammonium sulfate are often used for nesting, or super granules of urea are substituted and individually placed.

9.7.1.7 Starter

Starter fertilizer application is a form of band placement applied at planting in direct seed contact, below the seeds, or to the sides and below the seeds. Exact position is not implied by the title. *Pop-up* is another term sometimes used in starter terminology. It means direct seed application of fertilizer material at low rates to stimulate very early growth. Nutrient element rates in direct seed contact must be kept low to avoid germination and seedling damage.

9.7.1.7.1 Starter Fertilizer Benefits

Early season nutrient element availability is especially critical because young, limited root systems grow in cold, moist soils. Starter fertilization can help to assure that availability. It benefits plants by:

- Enhancing root and above-ground development, resulting in earlier cultivation, increased competition with weeds, reduced heat stress during pollination, and earlier harvest
- Providing quicker soil cover and decreasing runoff and erosion potential
- Reducing grain moisture content at harvest and cutting production costs
- Improving N use efficiency, increasing production efficiency, and reducing potential for water pollution
- Boosting yield and enhancing crop quality and, ultimately, farmer profit potential

9.7.1.8 Side-Dressing

Side-dressing involves placement of nutrient elements beside crop rows after emergence. Surface banding or some type of subsurface placement is usually employed. Fluids, solids, or anhydrous ammonia can be used.

TABLE 9.23
Placement Locations and Methods

Placement Location	Placement Method
Soil surface	Broadcast
	Stripped or dribbled
	Side-dressed and top-dressed
	Irrigation
Below soil surface	Broadcast, plowed under
	Broadcast, incorporated in varying degrees by other tillage operations
	Side-dressing
	Row application with seed, pop-up, or starter
	Banded apart from seed, starter
	Deep banding in fall or spring before seeding; also referred to as dual application, deep placement, knifing, tillage implement application, preplant banding, double shooting, root zone handing, etc.
	Irrigation
Directly onto plant	Foliar spray
	Fertigation with sprinkler systems

TABLE 9.24
Useful Equivalents for Estimating Application Rates for Small Areas

Unit	Equivalent[a]
1 tsp (level)	1/2 oz
2 tsp (level)	1 tbsp
3 tsp (level)	1 oz
1 pt	1.37 lb
1 qt	2.75 lb
1 gal	11.0 lb
1 pt liquid	1.046 lb

[a] The equivalents are based on a fertilizer with an average weight/unit of volume, such as superphosphate and most mixed fertilizers. Organics, except bone meal, are generally lighter, and chemical salts heavier than average.

TABLE 9.25
Converting Rates per Acre to Rates for Small Areas

lb/Acre	Rate/100 lb/100 ft^2	lb/100 ft of 36-In. Row
100	3 1/2 oz	0.7
200	7 1/2 oz	1.4
300	11 oz	2.1
400	14 3/4 oz	2.8
500	1 lb 2 1/2 oz	3.4
600	1 lb 6 oz	4.1
700	1 lb 10 oz	4.8
800	1 lb 13 oz	5.5
900	2 lb 1 oz	6.2
1000	2 lb 5 oz	6.9
2000	4 lb 10 oz	13.8

9.8 ORGANIC FERTILIZERS

TABLE 9.26
Organic Fertilizer Catalog

Organic Fertilizer	Nutrients Supplied	Rate of Application	Uses and Comments	Sold as
Blood meal, dried blood	Blood meal: 15% N, 1.3% P, 0.7% K; Dried blood: 12% N, 3% P, 0% K	Up to 3 lb/100 ft^2 (more will burn plants	Source of readily available N; add to compost to speed decomposition; repels deer rabbits; lasts 3 to 4 months	Blood meal, dried blood
Bone meal	3% N, 20% P, 0% K, 24 to 30% Ca	Up to 5 lb/100 ft^2	Excellent source of P; raises pH; raw form contains gelatin which is rich in N; lasts 6-12 months	Raw bone meal
Colloidal phosphate or soft phosphate	0% N, 18 to 22% P, 27% calcium, 1.7% iron silicas, 14 other trace minerals	Up to 10 lb/100 ft^2	More effective than rock phosphate on neutral soils; P available higher (2% immediately available) than for rock phosphate because of small particle size of colloidal clay base; half the pH-raising value of ground limestone; use in fall in garden and when planting bare-root trees in winter; lasts 2 to 3 yr	
Composted cow manure	2% N, 1% P, 1% K	40 lb/50 to 100 ft^2 as soil conditioner; 2 parts to 6 to 8 parts loam as potting mix	Low level of nutrients and slow release make it valuable as a soil conditioner and as winter fertilizer for houseplants that then need minimal feeding	Composted cow manure
Cottonseed meal	6% N, 2 to 3% P, 2% K	2 to 5 lb/100ft^2; trees: for each in. of trunk size, apply 2 to 4 cc. around drip line	Acidifies soil, so best for crops that prefer low pH	Cottonseed meal
Dolomite, dolomitic limestone	51% calcium carbonate, 40% magnesium carbonate	To raise pH one unit, use 7 lb on clay or sandy loam, 5.5 lb on sand, and 10 lb on loam soils per ft^2	Raises pH and adds Mg, which is needed for chlorophyll production and photosynthesis; repeated use may cause Mg excess	Dolomite, dolomitic limestone
Fish emulsion, fish meal	Meal: 10% N, 4 to 6% P, 1% K	Meal: up to 5 lb/100 ft^2; emulsion: dilute 20:1 with water	Meal: use in early spring, at transplanting, and any time plants need a boost; lasts 6 to 8 months; emulsion: apply as foliar spray in early morning or evening	Fish emulsion, fish meal, fish soluble
Granite dust, granite meal, crushed granite	0% N, 0% P, 3 to 5% K, 67% silica, 19 trace minerals	Up to 10 lb/100 ft^2	Very slowly available; releases potash more slowly than greensand; lasts up to 10 years; improves soil structure; use mica-rich type only	Granite dust, granite meal
Greensand, glauconite	0% N, 1% P, 5 to 7% K, 50% silica, 18 to 23% iron oxide, 22 trace minerals	Up to 10 lb/100 ft^2	Slowly available; lasts up to 10 yr; loosens clay soils; apply in fall for benefit during next season	Greensand, Jersey greensand

Guano (bat)	8% N, 4% P, 2% K average but varies widely; 24 trace minerals	Up to 5 lb/100 ft^2; 2 tbsp/pt potting soil; 1 lb/gal water for manure tea	Caves protect guano from leaching so nutrients are conserved	Quik Start, Bloomin' Wonder, Super Bat, Full Circle Bat, natural bat guano
Guano (bird)	13% N, 8% P, 2%K, 11 trace minerals	3 lb/100 ft^2; fruit trees: 3 to 6 oz/in. trunk diameter; houseplants: 1 to 2 oz/gal water	Especially good for roses, bulbs, azaleas, and houseplants	Plantjoy
Gypsum (calcium sulfate)	23 to 57% Ca, 17.7% S	Up to 4 lb/100 ft^2	Use when both Ca and S are needed and soil pH is already high; S will tie up excess Mg; helps loosen clay soils	Gypsum
Hoof and horn meal	14% N, 2% P, 0% K	Up to 4 lb/100 ft^2	High nitrogen source; much more slowly available than bloodmeal; good for fall-planted perennials; smelly; takes 4 to 6 wk to start releasing N; lasts 12 mo	Hoof and horn meal
Langbeinite	0% N, 0% P, 22% K, 22% S, 11% Mg	Up to 1 lb/100 ft^2	Will not alter pH; use where Ca and S are abundant and Mg and K are needed	Sul-Po-Mag, K-Mag
Leatherdust, leather meal	5.5 to 12% N, 0% P, 0% K	0.5 lb/100 ft^2	2% N is immediately available; balance releases slowly over growing season; does not burn or leach	Leathermeal, Nitro-10
Rock phosphate	0% N, 22% P, 0% K, 30% Ca, 2.8% Fe, 10% silica, 10 other trace minerals	Up to 10 lb/100 ft^2	Releases P best in acid soils below ph 6.2; slower release than colloidal phosphate; will slowly raise pH one unit or more	Rock phosphate, phosphate rock
Kelp meal, liquid seaweed	1% N, 0% P, 12% K	Meal: up to 1 lb/100 ft^2; liquid: dilute 25:1 with water for transplanting and rooting cuttings; 40:1 as booster and for fruit crops	Contains natural growth hormones, so use sparingly; best source of trace minerals; lasts 6 to 12 mo	Thorvin Kelp, FoliaGro, Sea Life, Maxicrop, Norwegian Seaweed, K-meal, liquid kelp
Sulfur	100% S	1 lb/100 ft^2 to lower pH one unit; as fungicide: dilute 3 tbsp/gal water	Lowers pH in alkaline soils; increases crop protein; ties up excess Mg	Sulfur, Dispersul

TABLE 9.27
Average Elemental Compositions (%) of Common Natural Organic Materials and Manures

Elemental Composition	N	P	K	Ca	Mg	S	Cl
			Organic Material				
Activated sewage sludge	6.0	1.0		1.8	0.9	0.4	0.5
Blood, dried	13.0			0.4			0.6
Bone meal (raw)	3.5	19.8		22.5	0.6	0.2	0.2
Bone meal (steamed)	2.0	12.2		23.6	0.3	0.2	
Castor pomace	6.0	0.6	0.4	0.4	0.3		0.3
Cocoa meal	4.0	0.6	2.1	0.4	0.6		
Cocoa shell meal	2.5	0.4	2.5	1.1	0.3		
Cocoa tankage	2.5	0.6	1.0	12			
Cottonseed meal	6.6	1.1	1.2	0.4	0.9	0.2	
Fish scrap (acidulated)	5.7	1.3		6.1	0.3	1.8	0.5
Fish scrap (dried)	9.5	2.6		6.1	0.3	0.2	1.5
Garbage tankage	9.5	0.6	0.8	3.2	0.3	0.4	1.3
Peanut meal	7.2	0.6	1.0	0.4	0.3	0.6	0.1
Peanut hull meal	1.2	0.2	0.7				
Peat	2.7			0.7	0.3	1.0	1.1
Peruvian guano	13.0	5.5	2.1	7.9	0.6	1.4	1.9
Process tankage	8.2		0.4		0.4		
Soybean meal	7.0	0.5	1.3	0.4	0.3	0.2	
Tankage, animal	7.0	4.3		11.1	0.3	0.4	0.7
Tobacco stems	1.5	0.2	4.2	3.6	0.3	0.4	1.2
Whale guano	8.5	2.6		6.4	0.3		
Manure	**N**	**P**	**K**	**Organic C**			
Dairy	0.7	0.1	0.5	30			
Goat	2.8	0.6	2.4	60			
Hog	1.0	0.3	0.7	30			
Horse	0.7	0.1	0.4	60			
Poultry	1.6	0.5	0.8	50			
Rabbit	2.0	0.6	1.0	50			
Sheep	2.0	0.4	2.1	60			
Steer	2.0	0.2	1.6	60			

TABLE 9.28
Fertilizer Nutrient Contents and C/N Ratios of Commercial Organic Products

	[lb/ton (%)]				
Material	**Nitrogen**	**Phosphate**	**Potash**	**Sulfur**	**Carbon/ Nitrogen Ratio**
Alfalfa pellets	54 (2.7)	10 (0.5)	56 (2.8)	4 (0.2)	15
Blood meal	260 (13)	40 (2)			3
Bone meal	60 (3)	400 (20)	10 (0.5)		
Cocoa shells	20 (1)	20 (1)	60 (3)		42
Cottonseed meal	120 (6)	40 (2)	40 (2)		7
Fish scraps, dried and ground	180 (9)	140 (7)			4
Hoof and horn meal	140–300	40 (2)			3
Average	220 (11)				
Linseed meal	100 (5)	40 (2)	20 (1)		8
Seaweed, ground	20 (1)	4 (0.2)	40 (2)	60 (3)	
Soybean meal	120 (6)	30 (1.4)	40 (2)		7
Tankage, rendered, dried, ground	80–180	180–400			7
Average	130 (6.5)	290 (14.5)			

TABLE 9.29
Typical Major Nutrient Element Contents (%) of Organic Materials

Organic Material	Water	Carbon	Nitrogen	Phosphorus	Potassium	Calcium
Human feces		1.0	0.2	0.3		
Cattle feces		0.3	0.1	0.1		
Pig feces		0.5	0.2	0.4		
Fresh cattle manure	60	8–10	0.4–0.6	0. 1–0.2	0.4–0.6	0.2–0.4
Composted cattle manure	35	30–35	1.5	1.2	2.1	2.0
Pig manure	80	5–10	0.7–1.0	0.2–0.3	0.5–0.7	1.2
Poultry manure	55	15	1.4–1.6	0.5–0.8	0.7–0.8	2.3
Garbage compost	40	16	0.6	0.2	0.3	1.1
Sewage sludge	50	17	1.6	0.8	0.2	1.6
Sugarcane filter cake	75–80	8	0.3	0.2	0.1	0.5
Castor bean cake	10	45	4.5	0.7	1.1	1.8

Note: kg nutrient per ton fresh manure = % nutrient content x 10.

Source: Rice: Nutrient Disorders and Nutrient Management, 2000, Potash & Phosphate Institute, Norcross, GA. With permission.

TABLE 9.30
Micronutrient Contents (lb/ton) of Organic Materials

Fertilizer	Quantities[a] (lb/ton)					
	Boron	Copper	Iron	Manganese	Molybdenum	Zinc
Manure				***Organic***		
Cow	0.03	0.01	0.27	0.02	0.002	0.03
Horse	0.03	0.01	0.08	0.02	0.002	0.03
Sheep	0.02	0.01	0.32	0.02	0.002	0.05
Pig	0.08	0.01	0.56	0.04	0.002	0.12
Poultry						
Cage layer	0.12	0.03	0.93	0.18	0.011	0.18
Broiler	0.08	0.06	2.0	0.46	0.007	0.25
Hay						
Legume	up to 5	0.02	0.2	0.2	0.006	0.1
Nonlegume		0.01		0.14		0.06
Straw		0.009		0.27		0.06
Average crop	0.2	0.01	0.2	0.4	0.01–0.001	0.05
Alfalfa pellets	0.09	0.02	0.6	0.06		0.03
Seaweed	0.01	0.01	0.04	0.1	0.002	0.02
			Inorganic			
Wood ashes	0.6	0.1	40	16		

[a] Fresh weight basis for manure and dry weight bases for others.

TABLE 9.31
Approximate Nutrient Element Levels for Manures

Manure Type		Nutrient Element Content					
		N	P_2O_5	K_2O	Cu	Mn	Zn
Solid Manure	Layer	27	22	12	—	—	—
from poultry	Broiler	53	58	37	0.4	0.5	0.5
(lb/ton)[a]	Turkey	53	58	34	0.4	0.5	0.5
Liquid Manure	Swine	40	23	20	0.05	0.25	0.25
from livestock	Dairy	29	14	27	—	—	—
lb/1,000 gal[b]	Beef	38	24	33	—	—	—

[a] Dry matter content ranges from 60 to 90%.
[b] Liquid weight based on 8.34 lb/gal.

Source: Crop Fertilization Based on North Carolina Soil Tests, 1997, North Carolina Department of Agriculture and Consumer Services, Raleigh.

TABLE 9.32
Average Element Content of Dung

Element	kg/ton
Nitrogen	4.0
Phosphorus as phosphate	2.5
Potassium as potash	5.5
Calcium	5.0
Magnesium	2.5
Sulfur	0.5
Boron	0.004
Copper	0.002
Manganese	0.04

TABLE 9.33
Approximate Major Element Composition of Manures

	Approximate Composition			
Source	Dry Matter (%)	Nitrogen (% dry weight)	Phosphate (% dry weight)	Potash (% dry weight)
Dairy	15–25	0.6–2.1	0.7–1.1	2.4–3.6
Feedlot	20–40	1.0–2.5	0.9–1.6	2.4–3.6
Horse	15–25	1.7–3.0	0.7–1.2	1.2–2.2
Poultry	20–30	2.0–4.5	4.5–6.0	1.2–2.4
Sheep	25–35	3.0–4.0	1.2–1.6	3.0–4.0
Swine	20–30	3.0–4.0	0.4–0.6	0.5–1.0

Source: *Knott's Handbook for Vegetable Growers*, 4th ed., 1997, John Wiley & Sons, New York. With permission.

9.9 INSTRUCTIONS FOR PREPARING ORGANIC FERTILIZER[5]

Organic fertilizers need not be expensive. You can make your own. This recipe, to the best of my knowledge, was created by Steve Solomon, founder of Territorial Seed Company. I have used it for 6 years with good results. Instead of buying components in small quantities, buy bulk bags (40 to 50 lb) at a farm supply or feed store. If you keep them dry, they will last many years. All measurements are shown in terms of volume, not weight.

4 parts seed meal
1 part dolomite lime
1/2 part bone meal or 1 part soft rock phosphate
1/2 part kelp meal

Seed meal provides N and smaller amounts of P and K. I like to use cottonseed meal, which costs about $13 for a 40-lb bag and is readily available. Some states prohibit its use in certified organic operations (not something a home grower needs to be concerned about). Other options are alfalfa meal, or rape/canola meal. The NPK value of cottonseed meal is about 6-2-1. In spring, I

substitute bloodmeal in place of some seed meal, since it acts more quickly. Try using three parts seed meal and one part bloodmeal.

Seed meals tend to be acidic, so lime is included to balance that. Dolomite limestone is roughly half magnesium carbonate ($MgCO_3$) and half calcium carbonate ($CaCO_3$). Calcitic limestone is pure calcium carbonate. Plants usually need more Ca than Mg. You might want to try 1/3 dolomite lime and 2/3 calcitic lime. If your soil is alkaline, you might experiment with reducing or eliminating the lime.

Bone meal and rock phosphate provide the bulk of the P component. Less bone meal (NPK 0-10-0) is required since it releases its P more readily. The advantage of using rock phosphate (NPK 0-3-0) is that it continues to contribute P to the soil over many years. Bone meal is easy to find. It is produced as a by-product of the beef industry. Rock phosphate is mined. Twenty pounds of bone meal cost about $5.

Kelp meal (NPK 0-0-10) contributes K and micronutrients. It tends to be more expensive than the other components; I recently paid $35 for a 50-lb bag. Another possible K source is Jersey greensand. It has the same advantages and liabilities as rock phosphate (very slow release) but does not supply micronutrients.

TABLE 9.34
Formulas for Balanced, All-Purpose Organic Fertilizer

Fertilizer Ratio ($N-P_2O_5-K_2O$)	Ingredients
2-3.5-2.5	1 part bone meal
	3 parts alfalfa hay
	2 parts greensand
2.5-2.5-4	3 parts granite dust
	1 part dried blood
	1 part bone meal
	5 parts seaweed
4-5-4	2 parts dried blood
	1 part phosphate rock
	4 pants wood ashes
3.5-5.5-3.5	2 parts cottonseed meal
	1 part colloidal phosphate
	2 parts granite dust
0-5-4	1 part phosphate rock
	3 parts greensand
	2 parts wood ashes
2-8-3	3 parts greensand
	2 parts seaweed
	1 part dried blood
	2 parts phosphate rock

REFERENCES

1. *Glossary of Soil Science*, 1987, Soil Science Society of America, Madison, WI.
2. *The Fertilizer Handbook*, 1982, Fertilizer Institute, Washington, D.C.
3. *Soil and Plant Phosphate*, 2000, International Fertilizer Association, Paris.
4. *Better Crops with Plant Food*, 85, 14, 2001.
5. Travis Saling, http://www.i4at.ordlib2/fertmake.htm

10 Plant Mineral Nutrition

10.1 BASIC PRINCIPLES

Plant mineral nutrition is a science that studies the effects of elements on plant growth and development, determines the forms and conditions of availability and uptake, and establishes the ranges of beneficial and detrimental effects. Scientists began to unravel the mysteries of how green plants grow in the 1800s. A number of theories were put forth to explain plant growth, and through observation and carefully crafted experiments, scientists began to learn what was required for normal growth and development.

It might be well to note that modern humus concept theories that relate to the forms in which elements exist in the soil and the forms that should be supplied to plants had their origins in theories developed by some of these early scientists. The ideas that the soil provided "food" for plants and that humus in the soil was the source of plant health still have their proponents. It is fairly well established that the form of an essential element, whether as an inorganic ion or originating from an organic matrix, is not a factor that determines the wellbeing of a plant. The combination of concentration and lability of an essential element determines a plant's nutritional status.

The early scientists discovered that the mass of a live plant was essentially composed of water and organic substances, and that total mineral matter constituted less than 10% and frequently less than 5% of the dry matter of most plants. The analysis of the mineral matter (ash) after the removal of water and destruction of the organic matter provided better understanding of the nutritional requirements of plants by revealing which elements were present in the ash and at what concentrations. By 1890, scientists established plant requirements for C, H, O, N, P, S, K, Ca, Mg, and Fe. Their absence or low availability led to plant death or poor growth after exhibiting visual symptoms. By the early 1900s, 10 of the now-known 16 essential elements required by plants had been identified, but no system existed to scientifically establish their absolute essentiality. Their presence was assumed to be related to their importance.

In 1939, two University of California plant physiologists, A.I. Arnon and P.R. Stout, published criteria for plant nutrient element essentiality — criteria that are still acknowledged today.[1] They established three criteria:

- Omission of the element in question must result in abnormal growth, failure to complete the life cycle, or premature death of the plant.
- The element must be specific and not replaceable by another.
- The element must exert its effect directly on growth or metabolism and not exert some indirect effect such as by antagonizing another element present at a toxic level.

Between 1922 and 1954, Mn, Cu, Zn, Mo, B, and Cl were determined to be essential. The 16 essential elements, their discoverers, and the discoverers of their essentiality are listed in Table 10.1. Plant physiologists today continue to apply the three requirements set forth by Arnon and Stout over 60 years ago in attempts to determine whether additional elements are essential plants. Recent plant nutrition studies suggest that two additional elements, nickel (Ni) and silicon (Si), should be added to the list, although many plant nutritionists have yet to be convinced that Ni and Si meet all the requirements for essentiality set by Arnon and Stout.[1]

The concentrations plants require for normal growth and development vary enormously (relative range is from 1 to 1 million) among 13 of the essential elements as shown in Table 10.2. It is not surprising that many essential elements were not identified until the purification of reagent chemicals was achieved, and the techniques of analytical chemistry brought detection limits below the milligram level.

Carbon, H, and O are derived from air and water. They are combined in a process known as photosynthesis that is exclusive to green (chlorophyll-containing) plants. In this energy-trapping process that takes place in the presence of light and chlorophyll, a molecule of water (H_2O) is split. One portion is combined with carbon dioxide (CO_2) to form a carbohydrate (CH_2O) and the other portion is released as an oxygen (O_2) molecule, as shown in the following basic equation:

$$nCO_2 + n(2H_2O) + \text{light} + \text{chlorophyll} \rightarrow n(CH_2O) + n(O_2)$$

The remaining 13 essential elements are derived primarily from the soil or growing medium. They are grouped into two categories based on their concentrations found in plants as either macronutrients (N, P, K, Ca, Mg, and S that have sufficiency requirements at relatively high concentrations), or micronutrients (B, Cl, Cu, Fe, Mn, Mo, and Zn that are required at relatively low concentrations).

Nitrogen can also be brought into leguminous plants by a process called nitrogen (N_2) fixation. Organisms that exist symbiotically as nodules on plant roots convert atmospheric N_2 into N compounds that can be utilized by the plants. Nitrogen fixation can supply most N requirements of leguminous plants under certain circumstances.

TABLE 10.1
Chronology of Discoveries of Essential Nutrient Elements

Element	Discoverer	Year	Discoverer of Essentiality	Year
C	[a]	—	DeSaussure	1804
H	Cavendish	1766	DeSaussure	1804
O	Priestley	1774	DeSaussure	1804
N	Rutherford	1772	DeSaussure	1804
P	Brand	1772	Ville	1860
S	[a]	—	von Sachs, Knop	1865
K	Davy	1807	von Sachs, Knop	1860
Ca	Davy	1807	von Sachs, Knop	1860
Mg	Davy	1808	von Sachs, Knop	1860
Fe	[a]	—	von Sachs, Knop	
Mn	Scheele	1774	McHargue	1922
Cu	[a]	—	Sommer	1931
		—	Lipman and MacKinnon	1931
Zn	[a]	—	Sommer and Lipman	1926
Mo	Hzelm	1782	Arnon and Stout	1939
B	Gay-Lussac and Thenard	1808	Sommer and Lipman	1926
Cl	Scheele	1774	Stout	1954

[a] Element known since ancient times.

Source: Plant Nutrition: An Introduction to Current Concepts, 1989, Jones and Bartlett, Boston.

TABLE 10.2
Average Concentrations of Mineral Nutrients in Plant Dry Matter Required for Adequate Growth

Mineral Nutrient	μmol/g dry wt.	mg/kg (ppm)	Percent	Relative Number of Atoms
Molybdenum	0.001	0.1	—	1
Copper	0.10	6	—	100
Zinc	0.30	20	—	300
Manganese	1.0	50	—	1,000
Iron	2.0	100	—	2,000
Boron	2.0	20	—	2,000
Chlorine	3.0	100	—	3,000
Sulfur	30	—	0.1	30,000
Phosphorus	60	—	0.2	60,000
Magnesium	80	—	0.2	80,000
Calcium	125	—	0.5	125,000
Potassium	250	—	1.0	250,000
Nitrogen	1,000	—	1.5	1,000,000

Source: Epstein, E., Mineral nutrition, in Bonner, J. and Varner, J.E., Eds., *Plant Biochemistry,* 1965, Academic Press, Orlando, FL.

10.2 ESSENTIAL NUTRIENT ELEMENTS, UPTAKE FORMS, AND RELATIVE CONCENTRATIONS IN PLANTS

TABLE 10.3
Nutrient Elements, Uptake, and Biochemical Functions

Nutrient Element	Uptake	Biochemical Functions
1st group C, H, O, N, S	In the form of CO_2, HCO_3^-, H_2O, O_2, NO_3^-, NH_4^+, N_2, SO_4^{2-}, SO_2. The ions from the soil solution, the gases from the atmosphere.	Major constituent of organic material; essential elements of atomic groups which are involved in enzymic processes; assimilation by oxidation-reduction reactions.
2nd group P, B, Si	In the form of phosphates, boric acid or borate, silicate from the soil solution	Esterification with native alcohol groups in plants; the phosphate esters are involved in energy transfer reactions.
3rd group K, Na, Mg, Ca, Mn, Cl	In the form of ions from the soil solution.	Nonspecific functions established osmotic potentials; more specific reactions in which the ion brings about optimum conformation of an enzyme protein (enzyme activation); bridging of the reaction partners; balancing anions; controlling membrane permeability and electro-potentionals.
4th group Fe, Cu, Zn, Mo	In the form of ions or chelates from the soil solution.	Present predominantly in a chelated form incorporated in prosthetic groups; enable electron transport by valency change.

TABLE 10.4
Nutrient Elements Required for Normal Growth, Typical Concentrations, Major Functions, and Usual Sources

Element	Typical Concentration (% dry wt.)	Usual Sources	Major Functions
Group I: Structural Components and Intermediates of Metabolism			
Carbon	44	Atmosphere	Organic compounds
Hydrogen	6	Atmosphere	Organic compounds
Oxygen	44	Atmosphere	Organic compounds
Nitrogen	2	CF, NF, Atm.[a]	Amino acids, proteins, co-enzymes
Sulfur	0.5	NF, CF	Amino acids, proteins.
Phosphorus	0.4	CF, NF	ATP, NADP (i.e., energy system)
Group II: Enzyme Activators			
Potassium	2.0	CF, NF	Activates about 60 enzymes; essential for protein synthesis; responsible for turgor and stomata movement
Calcium	1.5	NF, CF	Activates enzymes; essential for membrane permeability
Magnesium	0.4	NF, CF	Activates ATP; component of chlorophyll
Manganese	0.4	NF, CF	Activates enzymes; essential for photolysis of H_2O
Group III: Redox Reagents that Undergo Reduction/Oxidation via Multiple Valency			
Iron	0.015	NF	$Fe^{3+} + e \leftrightarrow Fe^{2+}$
Copper	0.002	NF	$Cu^{2+} + e \leftrightarrow Cu^{+}$
Molybdenum	0.002	NF	Reduction of nitrate (NO_3^-) by nitrate reductase and reduction of N_2 by nitrogenase of free living and no bacteria in legumes: $Mo^{+6} + e \leftrightarrow Mo^{5+}$
Group IV: Elements of Uncertain Function			
Boron	0.003	NF	Membrane activity?
Chlorine	0.01–2.0	NF	Osmosis, charge balance, photolysis of H_2O?
Silicon[b]	?	NF	May reduce transpiration
Zinc	?	NF	Protein synthesis; growth hormones; may be important in reproduction
Sodium	0.05–10.0	NF	May be essential for C4 photosynthesis

[a] Atm. = atmosphere; CF = commercial fertilizer; NF = native fertility.
[b] The need for Si and the role of Si are not universally accepted.

Source: *Plant Nutrition: An Introduction to Current Concepts*, 1989, Jones & Bartlett, Boston.

TABLE 10.5
Characteristics and Principal Forms of Uptake of Nutrient Elements Essential for Growth and Plant Contents

Element	Atomic No.	Atomic Wt.	Principal Forms for Uptake	Plant Contents[a]		
			Macronutrient			
Hydrogen	1	1	Water	6	60,000	
Carbon	6	12	Air CO_2, soil	45	40,000	
Oxygen	8	16	Water H_2O,air O_2	45	30,000	
Nitrogen	7	14	NH_4^+, NO_3^-	1.5	1,000	0.5–5
Potassium	19	39.1	K^+	1.0	250	0.5–5
Calcium	20	40.1	Ca^{2+}	0.5	125	0.05–5
Magnesium	12	24.3	Mg^{2+}	0.2	80	0.1–1
Phosphorus	15	31	$H_2PO_4^-$, HPO_4^{2-}	0.2	60	0.1–0.5
Sulfur	16	32.1	SO_4^{2-}	0.1	30	0.05–0.5
			Micronutrient			
Chlorine	17	35.5	Cl^-	100	3	100–10,000
Boron	5	10.8	H_3BO_3	20	2	2–100
Iron	26	55.9	$Fe,^{2+}$ Fe^{3+}	100	2	50–1,000
Manganese	25	54.9	Mn^{2+}	50	1	20–200
Zinc	30	65.4	Zn^{2+}, Zincate	20	0.3	10–100
Copper	29	63.5	Cu^{2+}	6	0.1	2–20
Molybdenum	42	96.0	MoO_4^{2-}	0.1	0.001	0.1–10

[a] Plant contents for macronutrients shown as %, mol/g, and Range (%); plant contents for micronutrients shown as ppm, mol/g, and ppm.

10.2.1 Factors Affecting Nutrient Element Concentrations[2]

Soil test levels and amounts of nutrient elements added by fertilizers, manures, residues, and soil amendments are key factors in nutrient element availability. However, the concentration of a nutrient element within a plant is the integrated value of all the factors that interacted to affect growth. Considering the number of factors that influence growth and resulting crop yields, it is surprising that plant analysis relationships hold as well as they do. Some of the relevant factors are discussed in the following paragraphs.

10.2.1.1 Soil Moisture

It is more difficult for plants to absorb nutrient elements at low soil moisture levels, so nutrient element contents will be lower. Sufficient nutrient elements should be added to prevent seasonal variations in moisture and other unfavorable environmental conditions.

10.2.1.2 Temperature

Low temperature reduces uptake of a number of elements including N, P, K, S, Mg, B, and Zn. In cooler climates, higher soil test levels or rates of applied nutrient elements must be used to achieve plant nutrient element concentrations comparable to those found in warmer climates. Under cooler conditions, root growth is slower and plant uptake processes are slowed. Also, releases of such elements as N, P, and S from organic matter through mineralization are slowed when temperatures are low.

10.2.1.3 Soil pH

Soil acidity and alkalinity influence the availabilities of many nutrient elements. For example, higher pH tends to lower Fe, Al, Zn, Mn, and B availability, and increases Mo availability. Lower pH makes it more difficult for plants to absorb Mg and P, but more Mn, Fe, and Al are absorbed.

10.2.1.4 Tillage and Placement

Conservation tillage practices may cause reduced uptake of nutrient elements including P and K. This is due in part to positional availability because much of the fertilizer is broadcast and remains on or near the surface. Band placement of nutrient elements near seed or deeper in the soil improves uptake by the plant. Side-band placement is effective for increasing nutrient uptake in early growth stages and may influence yield.

10.2.1.5 Compaction

Soil compaction can have major effects on ability to absorb nutrient elements. Compaction reduces oxygen in soil. Root energy production and consequent nutrient element absorption are slowed. Concentrating moderate amounts of readily available nutrients in starter fertilizer near seedlings can help overcome these problems.

Growth and yield responses to starter fertilizers even on high testing soils may be partially due to higher concentrations of nutrient elements intended to help overcome diminished ability to take up nutrient elements under compacted conditions.

10.2.1.6 Hybrid or Variety

Crop yield is the product of genetic capability and environmental factors. Hybrids or varieties vary greatly in their yield capabilities. For example, in an experiment in New Jersey, one corn hybrid yielded 312 bu per acre and another 227 bu per acre in the same environment. Obviously, their total nutrient element uptakes were much different.

Varieties or hybrids may vary widely in their nutrient element requirements and responses to environmental conditions. For instance, studies demonstrated significantly different corn hybrid responses to K knifed into the ridges for ridge-till corn. Differences in corn hybrid responses to starter P have also been documented. Corn hybrid differences in N uptake patterns, time of N application, and availability of ammonium-N further emphasize genetic effects on nutritional requirements. More information is required to determine differences in critical or sufficiency levels of nutrient elements for specific varieties and hybrids.

10.2.1.7 Interactions

High concentrations of one element may cause imbalances or deficiencies of other elements. The relationship between P and Zn is one example. A high amount of available P may reduce the amount of Zn absorbed. With a marginal Mg supply in the soil, an application of K may reduce Mg uptake to the point of deficiency in the plant. The concentration of K in the plant may be reduced by a high rate of ammonia-N.

10.2.1.8 Stages of Growth

The concentration of an element considered to be adequate changes as a plant grows and matures. Hence, it is important to sample plants at comparable and recognizable growth stages.

TABLE10.6
Uptake of Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, Boron, Copper, Iron, Manganese, Molybdenum, and Zinc by Various Crops

Crop (tons/acre)	N (kg)	P_2O_5 (kg)	K_2O (kg)	Ca (kg)	Mg (kg)	S (kg)	B (g)	Cu (g)	Fe (g)	Mn (g)	Mo (g)	Zn (g)
Alfalfa (18)	500	134	538	218	50	50	600	120	1200	600	24	830
Corn (10)	240	102	120	43	58	30	36	20	120	36	—	60
Cotton lint (1.7)	200	57	95	14	23	20	120	110	140	190	2	480
Peanuts (4.5)	270	45	92	20	25	21	—	60	480	400	—	—
Rice (7.8)	125	67	130	23	16	21	60	20	810	600	2	215
Soybeans (4.0)	350	65	180	29	27	22	—	—	—	—	—	—
Wheat (4.0)	130	46	180	18	20	17	36	43	380	120	—	180

Source: International Soil Fertility Manual, 1995, Potash & Phosphate Institute, Norcross, GA.

10.3 MOVEMENT OF NUTRIENT ELEMENT IONS IN SOIL

TABLE 10.7
Movement of Nutrient Element Ions in Soil and Their Uptake by Plants

Method	Mechanism of Movement in Soil	Ions
Mass flow	Ion movement with and in water as a result of rainfall, applied irrigation water, or water movement as a result of evapotranspiration	Nitrate (NO_3^-), chloride (Cl^-), calcium (Ca^{2+}), sulfate (SO_4^{2-})
Diffusion	Ion movement in soil solution driven by concentration gradients	Phosphate (PO_4^{3-}), potassium (K^+)
Root interception	Absorption of ions from the soil solution by plant root contact as a result of root movement (growth) through soil; extent of uptake depends on amount of root occupation and root characteristics	

TABLE 10.8
Relative Significance of Movements of Ions from Soil to Corn Roots

Element	Amount (lbs) Required for 150 Bu/Acre Corn	% Supplied by: Root Interception	Mass Flow	Diffusion
Nitrogen	170	1	99	0
Phophorus	35	3	6	94
Potassium	175	2	20	78
Calcium	35	71	29	0
Magnesium	40	38	50	12
Sulfur	20	5	95	0
Copper	0.1	10	40	50
Zinc	0.3	33	33	33
Boron	0.2	10	35	55
Iron	1.9	11	53	37
Manganese	0.3	33	33	33
Molybdenum	0.01	10	20	70

Source: Soil Nutrient Bioavailability: A Mechanistic Approach, 1984, John Wiley & Sons, New York.

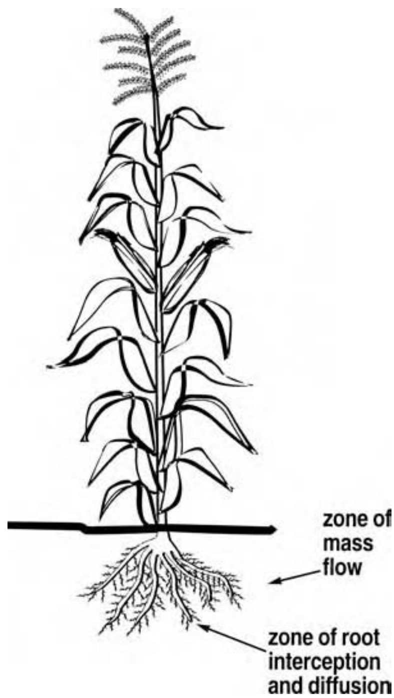


FIGURE 10.1 Movement of nutrient element ions in the soil by mass flow, root interception, and diffusion.

10.4 NUTRIENT ELEMENT SYMPTOMS[2]

10.4.1 Factors Affecting Nutrient Element Symptoms

Why do symptoms of a plant nutrient element deficiency occur? Because the amount of the nutrient element present in a form the plant can take up and use is insufficient. The reason may be that the soil was infertile and not enough of the nutrient element was added, but other factors affect uptake and lead to the appearance of symptoms.

10.4.1.1 Root Zones

Crops differ a great deal in their development of root systems, and a single crop will show variations in the numbers roots developed, depending on the environment and differences in plant genetics. Since some plant nutrient elements do not move very far in the soil, the extent of the root system will determine whether the plant acquires enough of vital nutrient elements. If root growth is shallow, plants may show deficiency symptoms even when the soil contains a good supply of nutrient elements. Dry surface soil conditions may also limit nutrient element uptake if most of the available nutrient elements are in that zone. This situation is called positional unavailability. When a deficiency symptom is noted, it is good practice to examine the roots to see whether a restricted root zone may be contributing to the deficiency.

10.4.1.2 Temperature

Many growers noted symptoms when plants were young, only to see the plants "grow out" of the symptoms as the growing season progressed. This may be caused by the effect of temperature on root growth. If soil and air temperatures are cold, plants grow very slowly, root systems are small, and nutrient element uptake is low. Also, when air temperatures are too

low or too high, photosynthesis and respiration rates are affected. For example, if temperatures are too high at night, respiration continues at a high rate, burning up sugars and limiting the accumulation of carbohydrates.

10.4.1.3 Acidity or Alkalinity

When a symptom appears, the degree of soil acidity or alkalinity of the soil in which the plant is growing should be evaluated. Acidity or alkalinity is often related to the cause of the symptom.

The solubilities and availabilities of many plant nutrient elements depend on soil pH. When the pH rises above 6.0 to 6.5, elements such as Fe, Mn, Zn, and B decrease in solubility perhaps to the point where the plants become deficient and show symptoms. Conversely, when soil pH is too acid (below 6.0), Mo becomes less soluble and a deficiency may occur. Because of the influence of pH on nutrient element availability, it is essential to learn the liming history when a symptom is observed. Over-liming is easy to do on sandy soils. When these soils are overlimed, symptoms of Fe, Mn, and Zn deficiency are likely to appear.

In some parts of the world, soils are naturally alkaline. This is often the case in arid regions where soils are only slightly weathered or where alkaline salts have accumulated. In areas of higher rainfall where outcroppings of limestone exist, soil pH may be above 7.0 and symptoms of Fe, Mn, and Zn deficiency may be seen.

Soils in arid regions may also have problems of excess salinity (soluble salts) or a condition known as black alkali (Na excess). These problems must be dealt with by establishing drainage, adding amendments if Na is involved, and leaching. Plants on such soils grow slowly, appear droughty, and may exhibit necrosis of leaf margins.

10.4.1.4 Varieties and Genetic Factors

Sometimes a deficiency symptom is noticed in one variety of a crop and absent in another. This is not uncommon, but is often overlooked. Differences in genetic make-up may affect a plant's ability to take up and utilize certain nutrient elements. One variety may show symptoms of deficiency while a variety growing beside it may lack symptoms.

10.4.1.5 Stage of Maturity

As a plant nears maturity, it starts to show signs of old age such as reddening, browning, or leaf tip or edge burn. What may be a sign of aging may be mistaken for a deficiency symptom. In fact, a relationship exists. As a plant grows older, it may run out of N or K and mature before reaches its full yield potential. Some crops require a delicate balance between the amount of N required for full yield and what may be too little or too much. Visual symptoms help us recognize problems and make corrections.

10.4.2 Summary of Essential Elements and Functions

Nitrogen is essential to the formation of amino acids, the building blocks of proteins.

Phosphorus is used by plants to form nucleic acids and other vital chemicals. It promotes root formation, early growth, early maturity, and seed production.

Potassium encourages root growth and appears to enhance disease resistance in crops. It also boosts fruit size and quality. In fact, cotton takes up and uses more K during boll fill than at any other time in its development.

Sulfur occupies a grey area between primary nutrient elements and micronutrients. Some call it the fourth primary nutrient element, mainly because wide areas of S deficiency exist all over the U.S. Sulfur is required for three amino acids critical to protein formation.

Boron is needed primarily at the growing points (meristematic cells) of plants, where it helps differentiate the structural components of new cells. Boron deficiency can cause reduced flower set and death of terminal growth. Deficiency is often induced by intensive crop production and irrigation, both common features of cotton culture. Boron is not mobile, and thus is needed continuously at all growing points. For that reason, a foliar source of B is an effective measure.

Chlorine assists in photosynthesis and enhances disease resistance.

Copper is a relative newcomer to the ranks of micronutrient inputs. Deficiency most often appears in crops grown in highly organic or sandy soil, and interferes with protein synthesis.

Iron is vital to photosynthesis, and deficiencies most often occur where excess Zn or Mn is present, soil pH is high (alkaline), or aeration is poor (highly compacted or poorly draining clay soils).

Manganese works with Fe during chlorophyll synthesis. Excess Mn can cause Fe deficiency. If a soil has too much Mn, it cannot be eliminated, but a foliar nutrient element blend can help maintain or restore the proper element balance.

Molybdenum is critical to N utilization. Without Mo, a plant cannot convert nitrate-nitrogen (NO_{3}-N) to amino acids. Deficiency can lead to poor vigor and stunting.

Zinc controls the synthesis of indoleacetic acid, an important plant growth regulator. Deficiency is most common in high pH, low organic, sandy soils and can cause reduced fruit set. High P concentrations can also lead to Zn deficiency. Again, a balanced input can help.

TABLE 10.9
Generalized Symptoms of Nutrient Element Deficiencies and Excesses

Element/Status	Symptoms
	Major Elements
Nitrogen	
Deficiency	Light green leaf and plant color; older leaves turn yellow and will eventually turn brown and die. Plant growth is slow; plants will mature early and be stunted.
Excess	Plants will be dark green; new growth will be succulent; susceptible if subjected to disease, insect infestation, and drought stress; plants will easily lodge; blossom abortion and lack of fruit set will occur.
Ammonium	
Toxicity	Plants fertilized with ammonium-nitrogen (NH_{4}-N) may exhibit ammonium toxicity symptoms, with carbohydrate depletion and reduced plant growth; lesions may appear on plant stems, along with downward cupping of leaves, decay of the conductive tissues at the bases of the stems, and wilting under moisture stress; blossom-end fruit rot will occur and Mg deficiency symptoms may also appear.
Phosphorus	
Deficiency	Plant growth will be slow and stunted; older leaves will have purple coloration, particularly on the undersides.
Excess	Phosphorus excess will not have a direct effect on plants but may produce visual signs of Zn, Fe, and Mn deficiencies. High P may also interfere with normal Ca nutrition and typical Ca deficiency symptoms may be present.
Potassium	
Deficiency	Edges of older leaves will appear burned, a symptom known as scorch. Plants will easily lodge and be sensitive to disease infestation. Fruit and seed production will be impaired and of poor quality.
Excess	Plants will exhibit typical Mg and possibly Ca deficiency symptoms due to cation imbalance.
Calcium	
Deficiency	Growing tips of roots and leaves will turn brown and die. The edges of leaves will look ragged; edges of emerging leaves will stick together. Fruit quality will be affected and blossom-end rot will appear on fruits.

TABLE 10.9 (CONTINUED)
Generalized Symptoms of Nutrient Element Deficiencies and Excesses

Element/Status	Symptoms
Excess	Plants may exhibit typical Mg deficiency symptoms; in cases of great excess, K deficiency may also occur.
Magnesium	
Deficiency	Older leaves will be yellow, with interveinal chlorosis (yellowing between veins) symptoms. Growth will be slow and some plants may be easily infested by disease.
Excess	Results in a cation imbalance with signs of Ca or K deficiency.
Sulfur	
Deficiency	Overall light green color of the entire plant; older leaves turn light green to yellow as the deficiency intensifies.
Excess	Premature senescence of leaves may occur.
	Micronutrients
Boron	
Deficiency	Abnormal development of growing points (meristematic tissue); apical growing points eventually become stunted and die. Flowers and fruits will abort. For some grain and fruit crops, yield and quality are significantly reduced
Excess	Leaf tips and margins turn brown and die.
Chlorine	
Deficiency	Younger leaves will be chlorotic and plants will easily wilt. A plant disease will infest wheat if Cl is deficient.
Excess	Premature yellowing of the lower leaves with burning of leaf margins and tips. Leaf abscission will occur and plants will easily wilt.
Copper	
Deficiency	Plant growth will be slow; plants will be stunted; young leaves will be distorted and growing points will die.
Excess	Iron deficiency may be induced with very slow growth. Roots may be stunted.
Iron	
Deficiency	Interveinal chlorosis on emerging and young leaves with eventual bleaching of the new growth. When severe, the entire plant may turn light green.
Excess	Bronzing of leaves with tiny brown spots a typical symptom on rice crops.
Manganese	
Deficiency	Interveinal chlorosis of young leaves while the leaves and plants remain generally green. When severe, the plants will be stunted.
Excess	Older leaves will show brown spots surrounded by chlorotic zones and circles.
Molybdenum	
Deficiency	Symptoms are similar to those of N deficiency. Older and middle leaves become chlorotic first, and in some instances, leaf margins are rolled and growth and flower formation are restricted.
Excess	Not common.
Zinc	
Deficiency	Upper leaves will show interveinal chlorosis with whitening of affected leaves. Leaves may be small and distorted and form rosettes.
Excess	Iron deficiency will develop.

10.5 MICRONUTRIENT ELEMENTS

TABLE 10.10
Crops Susceptible to Micronutrient Deficiencies

Boron	Copper	Iron	Manganese	Molybdenum	Zinc
Alfalfa[a]	Alfalfa	Peanuts	*Barley*	Alfalfa	Maize
Cotton	*Barley*	Sorghum	Oats	*Clover*	*Rice*
Peanuts	*Oats*	Soybean	Sorghum	Soybean	Sorghum
Sugar beet	Rice	Sudan grass	*Soybean*		Soybean
	Wheat		Sudan grass		Sudan grass
			Sugar beet		
			Wheat		

[a] Italics indicates crops that are often treated.

TABLE 10.11
Estimated Occurrence of Micronutrient Deficiencies[a]

	Estimated Deficiency Degree and Occurrence (%)		
Micronutrient	Acute	Latent[b]	Total
Boron	10	20	30
Copper	4	10	14
Iron	—	3	3
Manganese	1	9	10
Molybdenum	3	12	15
Zinc	25	24	49

[a] Based on 190 field trials with maize, rice, wheat, and barley in 15 countries.
[b] Test crop did not necessarily respond to application of micronutrient.

TABLE 10.12
Relative Sensitivities of Selected Crops to Micronutrient Deficiencies

	Sensitivity to Micronutrient Deficiency					
Crop	Boron	Copper	Iron	Manganese	Molybdenum	Zinc
Alfalfa	High	High	Medium	Medium	Medium	Low
Barley	Low	Medium	High	Medium	Low	Medium
Bean	Low	Low	High	High	Medium	High
Clover	Medium	Medium	—[a]	Medium	Medium	Low
Corn	Low	Medium	Medium	Medium	Low	High
Grass	Low	Low	High	Medium	Low	Low
Oat	Low	High	Medium	High	Low	Low
Rye	Low	Low	—	Low	Low	Low
Sorghum	Low	Medium	High	High	Low	High
Soybean	Low	Low	High	High	Medium	Medium
Sudan grass	Low	High	High	High	Low	Medium
Sugar beet	High	Medium	High	Medium	Medium	Medium
Wheat	Low	High	Low	High	Low	Low

[a] Inadequate available data to categorize into low, medium, or high sensitivity groups.

TABLE 10.13
Agronomic Crop Species Sensitive to Deficient or Excessive Levels of Micronutrients

Micronutrient	Sensitive to Deficiency	Sensitive to Excess
Boron	Legumes, cotton, and sugar beet	Cereals
Chlorine	Cereals and sugar beet	
Copper	Cereals (oats) and alfalfa	Cereals and legumes
Iron	Sorghum, soybean, and clover	Rice and tobacco
Manganese	Cereals (oats), legumes, soybean, sugar beet	Cereals and legumes
Molybdenum	Legumes	Cereals
Zinc	Cereals (corn), legumes, grasses,	Cereals and soybean

TABLE 10.14
Soil Conditions and Crops Commonly Affected by Micronutrient Deficiencies

Micronutrient	Sensitive Crops	Soil Conditions for Deficiency
Boron	Alfalfa, clover, cotton, peanut, sugar beet	Acid sandy soils low in organic matter, overlimed soils, organic soils
Copper	Corn, small grains	Organic soils, mineral soil high in pH and organic matter
Iron	Clover, sorghum, soybean	Leached sandy soils low in organic matter, alkaline soils, soils high in phosphorus
Manganese	Alfalfa, small grains, soybean, sugar beet	Leached acid soils, neutral to alkaline soils high in organic matter
Zinc	Corn, sorghum	Leached acid sandy soils low in organic matter, neutral to alkaline soils and soils high in phosphorus

TABLE 10.15
Interactions of Major Nutrient and Trace Elements in Plants

Major Element	Antagonistic Elements	Synergistic Elements
Calcium	Aluminum, barium, beryllium, boron, cadmium, cesium, chromium, cobalt, copper, fluorine, iron, lead, lithium, manganese, nickel, strontium, zinc	Copper, manganese, zinc
Magnesium	Aluminum, barium, beryllium, chromium, cobalt, copper, fluorine, iron, manganese, nickel, zinc	Aluminum, zinc
Phosphorus	Aluminum, arsenic, boron, beryllium, cadmium, chromium, copper, fluorine, iron, lead, manganese, mercury, molybdenum, nickel, rubidium, scandium, silicon, strontium, zinc	Aluminum, boron, copper, fluorine, iron, manganese, molybdenum, zinc
Potassium	Aluminum, boron, cadmium, chromium, fluorine, manganese, mercury, molybdenum, rubidium	
Sulfur	Arsenic, barium, iron, lead, molybdenum, selenium	Fluorine, iron
Nitrogen	Boron, copper, fluorine	Boron, copper, iron, molybdenum
Chlorine	Bromine, iodine	

TABLE 10.16
Typical Concentrations of Micronutrients in Foliages of Normal Plants

Micronutrient	Dry Matter Content (mg/kg)	Cell Sap Content (mM)[a]	Nutrient Solution (mM)[b]
Boron	15–100	0.2–1.3	0.05
Chlorine	100–1,000	0.4–1.0	0.1
Copper	5–15	0.01–0.03	0.001
Iron	50–300	0.15–0.75	0.1
Manganese	25–250	0.06–0.6	0.01
Molybdenum	0.5–5	0.004–0.075	0.0005
Zinc	15–75	0.03–0.15	0.002

[a] Value merely indicates in round numbers the total aqueous concentration possible without regard to insoluble, lipid, or other structural fractions.
[b] Typical nutrient solution concentrations.

TABLE 10.17
Sufficient Micronutrient Content (mg/kg) of Plants at Weeks 7 to 8 Growth Stage

Crop	Boron	Copper	Iron	Manganese	Molybdenum	Zinc
Barley	5–10	5–10	21–200	25–150	0.10–0.3	15–60
Cotton	20–80	8–20	50–350	35–150	0.60–2.0	25–80
Groundnut	25–70	7–15	—	50–200	0.50–1.0	20–70
Maize	6–15	6–15	11–300	35–150	0.15–0.4	25–70
Oats	5–10	5–10	62–204	35–150	0.15–0.4	20–70
Rice	6–15	7–12	>80	40–150	0.40–1.0	30–70
Rye	4–10	5–10	—	20–100	0.10–0.3	15–60
Sorghum	5–15	5–12	50–250	25–150	0.15–0.3	15–60
Soybean	25–60	10–20	21–300	30–150	0.50–1.0	25–60
Sunflower	35–100	10–20	79–113	25–100	0.30–1.0	30–80
Wheat	5–10	5–10	21–200	35–150	0.10–0.3	20–70

10.6 MICRONUTRIENTS

TABLE 10.18
Classification of Micronutrients and Trace Elements as Essential Plant Nutrient Elements or Toxins

Element	Essential to Plants	Toxic to Plants
Micronutrient		
Boron	Yes	Yes
Copper	Yes	Yes
Manganese	Yes	Yes
Molybdenum	Yes	Yes
Zinc	Yes	Yes
Trace Element		
Antimony	No	?
Arsenic	No	Yes
Barium	No	Low
Beryllium	No	Yes
Bismuth	No	Yes
Cadmium	No	Yes
Chromium	No	Yes
Cobalt	Yes	Low
Lead	No	Yes
Mercury	No	No
Nickel	Possibly	Yes
Selenium	Yes	Yes
Silver	No	No
Tin	No	?
Tungsten	No	?
Vanadium	Yes	Yes

Note: Toxicity considers the likelihood of uptake of the element.

TABLE 10.19
Approximate Concentrations (mg/kg Dry Wt.) of Micronutrients and Trace Elements in Mature Leaf Tissue

Micronutrient/ Trace Element	Deficient or Normal	Sufficient or Toxic	Excessive
Antimony	—	7–50	150
Arsenic	—	1–1.7	5–20
Barium	—	—	500
Beryllium	—	<1–7	10–50
Boron	5–30	10–200	5–200
Cadmium	—	0.05–0.2	5–30
Chromium	—	0.1–0.5	5–30
Cobalt	—	0.02–1	15–50
Copper	2–5	5–30	2–100
Fluorine	—	5–30	50–500
Lead	—	5–10	30–300
Lithium	—	3	5–50
Manganese	15–25	20–300	300–500
Molybdenum	0.1–0.3	0.211	0–50
Nickel	—	0.1–5	10–100
Selenium	—	0.001–2	5–30
Silver	—	0.5	5–10
Thalliu	—	—	20
Tin	—	—	60
Titanium	0.2–0.5	0.5–2.0	50–200
Vanadium	—	0.2–1.5	5–10
Zinc	10–20	27–150	100–400
Zirconium	0.2–0.5	0.5–2.0	15

Source: *Trace Elements in Soils and Plants*, 3rd ed., 2000, CRC Press, Boca Raton, FL. With permission.

TABLE 10.20
Approximate Uptake of Micronutrients and Trace Elements

Micronutrient/Trace Element	Uptake (g/ha)
Manganese, iron	500
Zinc, boron	200
Copper	100
Molybdenum	10
Cobalt	1
Selenium	0.02

TABLE 10.21
General Effects of Micronutrient and Trace Element Toxicity on Common Cultivars

Trace Element	Symptoms	Sensitive Crops
Aluminum	Overall stunting, dark green leaves, purpling of stems, deaths of leaf tips and coralloid, damaged root systems	Cereals
Arsenic	Red-brown necrotic spots on old leaves, yellowing and browning of roots, depressed tillering, wilting of new leaves	Legumes, brome grass
Beryllium	Inhibition of seed germination and reduced growth, degradation of protein enzymes	
Boron	Margin or leaf tip chlorosis, browning of leaf points, decaying growing points, wilting and dying-off of older leaves; in severely affected pine trees, necrosis occurs on needles near the ends of shoots and in top halves of trees	Cereals
Cadmium	Brown margin of leaves, chlorosis, reddish veins and petioles, curled leaves, and brown stunted roots; severe reduction in growth of roots, tops, and number of tillers (in rice); reduced conductivity of stems caused by deterioration of xylem tissues	Legumes (beans, soybeans)
Chromium	Chlorosis of new leaves, necrotic spots and purpling, injured root growth	
Cobalt	Interveinal chlorosis in new leaves followed by induced Fe chlorosis and white leaf margins and tips and damaged root tips	
Copper	Dark green leaves followed by induced Fe chlorosis; thick, short, or barbed wire roots; depressed tillering	Cereals and legumes
Fluorine	Margin and leaf tip necrosis, and chlorotic and red-brown points of leaves	
Iron	Dark green foliage, stunted growth of tips and roots, dark brown to purple leaves of some plants (e.g., bronzing disease of rice)	Rice, tobacco
Lead	Dark green leaves, wilting of older leaves, stunted foliage, and brown short roots	
Manganese	Chlorosis and necrotic lesions on old leaves, blackish or red necrotic spots, accumulation of MnO particles in epidermal cells, drying tips of leaves, and stunted roots and plant growth	Cereals, legumes
Mercury	Severe stunting of seedlings and roots, browning of leaf points	Sugar beet, maize
Molybdenum	Yellowing or browning of leaves, depressed root growth and tillering	Cereals
Nickel	Interveinal chlorosis (caused by Fe-induced deficiency in new leaves), gray-green leaves, and brown and stunted roots and plant growth	Cereals
Rubidium	Dark green leaves, stunted foliage, increasing numbers of shoots	
Selenium	Interveinal chlorosis or black spots at Se content of about 4 ppm, and complete bleaching or yellowing of younger leaves at higher Se content, pinkish spots on roots	
Thallium	Impairment of chlorophyll synthesis, mild chlorosis and slight cupping of leaves, reduced germination of seeds and growth of plants	Tobacco, cereals
Titanium	Chlorosis and necrosis of leaves, stunted growth	Beans
Zinc	Chlorotic and necrotic leaf tips, interveinal chlorosis in new leaves, retarded growth of entire plants, injured roots resemble barbed wire	Cereals

Source: *Trace Elements in Soils and Plants*, 3rd ed., 2000, CRC Press, Boca Raton, FL. With permission.

TABLE 10.22
Forms and Principal Functions of Essential Micronutrients and Trace Elements

Element	Constituent	Function
Aluminum[a]	—	Controlling colloidal properties in cells, possible activation of some dehydrogenases and oxidases
Arsenic[a]	Phospholipid (in algae)	Metabolism of carbohydrates in algae and fungi
Boron	Phosphogluconate	Metabolism and transport of carbohydrates, flavonoid synthesis, nucleic acid synthesis, phosphate utilization, and polyphenol production
Bromine[a]	Bromophenols (in algae)	—
Cobalt	Cobalamide coenzyme	Symbiotic N_2 fixation, possibly also in non-nodulating plants, valence changes, stimulation of synthesis of chlorophyll and proteins
Copper	Various oxidases, plastocarbohydrate	Oxidation, photosynthesis, protein and cyanins, centroplasmin metabolism, possibly involved in symbiotic N_2 fixation and valence changes
Fluorine	Fluoroacetate (in a few species)	Citrate conversions
Iron	Hemoproteins and nonheme	Photosynthesis, N_2 fixation, valence changes, iron proteins, dehydrogenases, and ferredoxins
Lithium[a]	—	Metabolism in halophytes
Manganese	Many enzyme systems	Photoproduction of oxygen in chloroplasts and indirectly on NO_3 reduction
Molybdenum	Nitrate reductase, nitrogenase, oxidases, and molybdoferredoxin	N_2 fixation, NO_3 reduction, and valence changes
Nickel[a]	Enzyme urease (in *Canavalia* seeds)	Possibly in action of hydrogenase and translocation of N
Rubidium[a]	—	Function similar to that of K in some plants
Selenium[a]	Glycene reductase (in *Clostridium* cells)	—
Silicon	Structural components	—
Strontium[a]	—	Function similar to that of Ca in some plants
Titanium[a]	—	Possibly photosynthesis and N_2 fixation
Vanadium	Porphyrins	Lipid metabolism, photosynthesis (in green algae), and possibly in N_2 fixation
Zinc	Anhydrases, dehydrogenases, proteinases, and peptidases	Carbohydrate and protein metabolism

[a] Elements known to be essential for some groups or species and whose general essentialities need confirmation.

Source: *Trace Elements in Soils and Plants*, 3rd ed., 2000, CRC Press, Boca Raton, FL. With permission.

10.7 TRACE ELEMENTS

TABLE 10.23
Average Contents of Four Trace Elements in Dry Matters of Crops Grown Side by Side

Crop	Part Sampled	Cadmium (ppm)	Lead (ppm)	Cobalt (ppm)	Selenium (ppb)
Spring wheat	Grain	0.089 ± 0.064	0.06 ± 0.02	0.033 ± 0.042	4.7 ± 0.8
	Straw	0.258 ± 0.174	0.67 ± 0.37	0.049 ± 0.051	6.1 ± 2.3
Winter wheat	Grain	0.058 ± 0.017	0.07 ± 0.03	0.041 ± 0.040	—
	Straw	0.253 ± 0.153	0.46 ± 0.22	0.056 ± 0.063	—
Oats	Grain	0.026 ± 0.018	0.10 ± 0.04	0.027 ± 0.023	5.7 ± 1.3
	Straw	—	—	0.561 ± 0.28	0.078 ± 0.080
Barley	Grain	0.0321 ± 0.024	0.10 ± 0.06	0.021 ± 0.016	4.8 ± 0.9
	Straw	—	—	0.53 ± 0.22	0.054 ± 0.046
Rye	Grain	—	—	0.20 ± 0.17	0.047 ± 0.068
	Straw	0.130 ± 0.069	0.50 ± 0.30	0.0641 ± 0.081	—
Timothy, silage	First cut	0.034 ± 0.015	0.40 ± 0.28	0.0681 ± 0.089	6.5 ± 2.6
	Second cut	0.040 ± 0.019	0.64 ± 0.42	0.1101 ± 0.120	8.5 ± 3.5
Timothy	Dry hay	0.035 ± 0.023	0.42 ± 0.27	0.061 ± 10.068	6.2 ± 3.2
	Fresh growth	0.058 ± 0.029	1.14 ± 0.86	0.084 ± 10.059	11.0 ± 4.9
Ryegrass, silage	First cut	0.079 ± 0.032	0.70 ± 0.45	0.22 ± 10.37	9.3 ± 3.6
	Second cut	0.103 ± 0.042	1.55 ± 1.86	0.29 ± 10.56	12.4 ± 3.4
Red clover	Dry hay	0.083 ± 0.084	0.63 ± 0.25	0.53 ± 0.81	6.0 ± 3.1
	Fresh growth	0.108 ± 0.095	1.131 ± 1.04	0.55 ± 1.02	9.3 ± 4.3
Sugar beet	Root	0.203 ± 0.083	0.14 ± 0.08	0.10 ± 0.08	—
	Tops	0.687 ± 0.281	1.25 ± 0.98	0.24 ± 0.16	—

Note: Mean ± standard deviation.

10.8 HEAVY METALS

TABLE 10.24
Heavy Metals and Sources

Heavy Metal	Sources
Arsenic	Pesticides, coal and petroleum wastes, mine tailings
Cadmium	Electroplating, paint residues, plastics, and batteries
Chromium	Stainless steel, chrome-plated products, paints, fire brick
Copper	Mine tailings, copper dust, fly ash, fertilizers
Lead	Batteries, wet and dry air deposition, steel mill residues
Mercury	Catalysts for industrial processes, pesticides, metals
Nickel	Wet and dry air deposition, electroplating, batteries
Zinc	Batteries, galvanized metals, brass and rubber production

Source: Compost Organics: Buyers Guide, 1997–1998, Composting News, Mentor, OH.

TABLE 10.25
Cumulative Heavy Metal (Trace Element) Additions (kg/ha) to Soil Based on Cation Exchange Capacity

	Cation Exchange Capacity (meq/100 g)		
Heavy Metal	**<5**	**5 to 15**	**>15**
Cadmium	5.6	11.2	22.4
Nickel	56	112	224
Copper	140	280	560
Zinc	280	560	1,120
Lead	560	1,120	2,240

TABLE 10.26
Soil–Plant Transfer Coefficients for Heavy Metals

Element	Soil–Plant Transfer Coefficient
Arsenic	0.01–0.1
Beryllium	0.01–0.1
Cadmium	1–10
Chromium	0.01–0.1
Cobalt	0.01–0.1
Copper	0.1–10
Lead	0.01–0.1
Mercury	0.01–0.1
Nickel	0.1–1.0
Selenium	0.1–10
Thallium	1–10
Tin	0.01–0.1
Zinc	1–10

Source: *Heavy Metals in Soils*, 2nd ed., 1995, Blackie Academic, London.

TABLE 10.27
Removal of Trace Heavy Metals from Soil by Crops

Trace Element	Content of Soil (kg/ha)	Output with Planting			
		Reference (g/ha, %)[a]		Accumulator (g/ha, %)[a]	
Cadmium	1.5	1	0.06	100	10.0
Chromium	150	50	0.03	500	0.3
Copper	45	100	0.2	500	1.0
Lead	75	100	0.1	500	0.6
Manganese	810	1,000	0.1	5,000	0.6
Molybdenum	6	30	0.5	250	4.0
Nickel	39	50	0.1	100	0.3
Zinc	135	400	0.3	1,500	1.0

[a] As percent of total content of soil.

Source: *Trace Elements in Soils and Plants*, 2nd ed., 1994, CRC Press, Boca Raton, FL.

TABLE 10.28
Relative Heavy Metal Accumulation in Plants[a]

Heavy Metal	High Accumulators	Low Accumulators
Cadmium	—	Corn
Copper	Sugar beet, certain barley cultivars	—
Lead	Ryegrass, celery, corn	Some barley cultivars
Nickel	Sugar beet, ryegrass	Corn, barley cultivars
Zinc	Sugar beet	—

[a] Cadmium and lead in edible portions; copper, nickel, and zinc in leaves.

TABLE 10.29
Maximum Heavy Metal Concentrations per USEPA Regulations for Sludge Sold in Bulk for Land Application

Heavy Metal	Maximum Concentration (mg/kg)
Arsenic	75
Cadmium	85
Copper	4,300
Lead	840
Mercury	57
Molybdenum	75
Nickel	420
Selenium	100
Zinc	7,500

TABLE 10.30
Frequency of Monitoring per USEPA Regulations and Based on Annual Rate of Application of Sewage Sludge

Amount of Sewage Sludge (metric tons/yr)	Monitoring Frequency
<290	Annually
290 < 1,500	Quarterly
1,500 <15,000	Bimonthly
15,000 +	Monthly

10.9 SUMMARY: PLANT NUTRITION AND ESSENTIAL MAJOR NUTRIENT ELEMENTS

10.9.1 Nitrogen (N)

The atomic number of nitrogen is 7; its atomic weight is 14.01. Rutherford discovered it in 1772 and de Saussure proved it essential to plants in 1804.

10.9.1.1 Nitrogen in Soil

Most N (98%) is found in soils and is associated with organic material. Total N levels in soils range from 0.02% in subsoils to 2.5% in peat, but the plowed layers of most cultivated soils contain 0.02 to 0.04% N by weight. However, due to continuous changes in availability, determinations of soil N levels are of limited use to predict short-term availability to plants.

Changes in oxidation states occur naturally due to chemical, biochemical, and microbial processes. These reactions form the dynamic N cycle. The different N forms have oxidation levels of +5 in N_2O_5 and HNO_3; +4 in NO_2; +3 in N_2O_3 and HNO_2; +2 in NO; +1 in N_2O, HNO, and H_2N_2O; 0 in N_2; −1 in NH_2OH; −2 in NH_2-NH_2; and −3 in NH_3.

Soil N is found in three main fractions: (1) organic matter; (2) ammonium (NH_4^+) ions fixed on exchange sites of clay minerals; and (3) ammonium and nitrate (NO_3^-) ions in soil solution. The forms of N that are important to plant nutrition are ammonium (NH_4), nitrite (NO_2), and nitrate (NO_3). Both nitrate and ammonium are taken up by plants and constitute the major crop fertilizer forms of N. Nitrite is toxic to plants at very low levels (below 5 ppm) and generally becomes a factor only when environmental or cultural practices or chemicals affect the nitrification processes in the soil.

10.9.1.2 Soil Dynamics

Nitrogen in soil may be (1) transformed by mineralization (conversion of organic into inorganic N), followed by nitrification (conversion of ammonium into nitrate); (2) incorporated by symbiotic fixation (conversion of the N_2 gas into ammonia or ammonium); or (3) lost by denitrification (transformation of nitrate into N gas), ammonia volatilization (change of ammonium into N_2 gas), dissimilatory nitrite reduction (transformation of nitrite into nitrous oxide), or plant uptake (mainly ammonium and nitrate). The rates of these natural transformations may be altered by aerobic and anaerobic conditions, soil pH, temperature, chemical inhibitors, or certain fungicides and pesticides.

Nitrate is the primary N form absorbed by plants due to rapid conversion of ammonium in the soil to that form. Nitrification involves two steps. Bacteria (*Nitrosomonas* spp.) oxidize ammonium into nitrite (Step 1), and then *Nitrobacter* bacteria transform nitrite to nitrate (Step 2). Because Step 2 proceeds faster than Step 1 under normal conditions, nitrite does not accumulate in soils unless this process is blocked at the nitrite step by some environmental or cultural practice. Nitrification requires oxygen and releases hydrogen ions, thereby acidifying the soil over time and requiring lime to adjust the acidification of the soil.

Higher plants and microorganisms compete for N in soils. Because microorganisms are more efficient in intercepting N, its availability for plant growth depends on the soil carbon:nitrogen (C:N) ratio. When C:N > 30:1, N is immobilized by the decomposition of organic residue by soil microbes, while at 20:1 < C:N, limited immobilization and release of mineral N into the soil environment occur. N is available for plant uptake at C:N < 20:1. In order to increase N available for plant uptake, fertilizers containing N are routinely applied to cropped soils.

10.9.1.3 Fertilizers

Nitrogen fertilizers are usually grouped by the forms of N. Urea-based fertilizers include granular urea and liquid solutions of urea–ammonium nitrate, urea–ammonium phosphate, urea–ammonium sulfate, urea–nitric phosphate, urea phosphate, water-soluble urea formaldehyde, methylene–diurea,

dimethylenetriurea, and stabilized urea formaldehyde. Urea is usually rapidly converted to ammonium, which can be absorbed by plants in the ammonium form or as nitrate, if nitrification converts the ammonium to the nitrate form prior to absorption.

Ammonium-based fertilizers include gaseous anhydrous ammonia, granular ammoniated superphosphate, ammonium chloride, ammonium nitrate, ammonium nitrate–limestone, diammonium phosphate, monoammonium phosphate, ammonium phosphate nitrate, ammonium phosphate sulfate, ammonium polyphosphate, and ammonium sulfate. Ammonium may be absorbed by the plant or converted to nitrate before absorption. If negatively charged clay and humus particles are present in the soil, ammonium is less likely to leach due to its positive charge.

Nitrate-based fertilizers include calcium–ammonium nitrate solutions, granular calcium nitrate, potassium nitrate, magnesium nitrate, and sodium nitrate. Nitrate is not strongly bound to soil colloids, and is therefore prone to leaching during rainfall or irrigation. Organic N-containing fertilizers include dried blood, castor bean pomace, cottonseed meal, dried fish scraps, bird guano, manure, and sewage sludge. These N sources release ammonium upon decomposition.

Because N fertilizers are applied in fairly large quantities to cropland soils, they can exert marked effects on soil pH. Urea and ammonium-based fertilizers have strong acidification effects on bulk soils. This acidification results from release of protons during nitrification or absorption of ammonium by the roots. Similarly, organic N sources exert acidifying effects through mineralization. Continued long-term use of ammoniacal or urea-based N fertilizers must be accompanied by a regular liming program if soil acidity problems are to be avoided. The main factors of concern due to decreased soil pH are increased risks of Al and Mn toxicities. The use of nitrate-based fertilizers results in a temporary increase in soil pH.

10.9.1.4 Uptake and Assimilation by Higher Plants

Nitrate and ammonium should be regarded as separate nutrient elements due to their different reactions in plants. It is generally recognized that ammonium *greens* a plant while nitrate *grows* a plant. Ammonium is toxic to plants when absorbed and must be combined with carbon to form N compounds to prevent it from damaging the plants. If ammonium is supplied either through fertilizer application or rapid organic matter decomposition in amounts that take carbon normally utilized in the growth process, smaller plants will result. Because ammonium is incorporated into N compounds in the roots first, the first impact of high levels of ammonium will be reduced root growth. When the root system's ability to detoxify the absorbed ammonium is overloaded, ammonium ions will be translocated to the top portions of the plants. The carbon used for leaf and stem growth will be diverted to detoxify the absorbed ammonium.

Ammonium uptake is optimal at neutral pH; lower uptake with increasing acidity has been observed due to the competition between hydrogen (H^+) and ammonium (NH_4^+) ions for binding sites on plant roots. As the hydrogen ion concentration increases (or pH decreases), its competition with ammonium becomes more intense. The uptake mechanism for ammonium ions is currently unknown.

Nitrate is taken up in plants via both passive and active absorption in large amounts. It is continually absorbed as long as it exists in the soil. Nitrate uptake can be depressed by ammonium. It decreases at pH levels below 4.5 and above 6.0. Reductions in uptake at high pH may be due to the competitive effects of hydroxyl ions. Nitrate and ammonium uptake are both temperature-dependent, with uptake increasing as temperature increases.

10.9.1.5 Nitrate Translocation

Nitrate is transported upward through the xylem. Simultaneously, organic anion synthesis increases with a corresponding increase in accumulated inorganic cations (Ca, Mg, K, and Na) in roots. After absorption, nitrate can be stored in vacuoles or incorporated into organic molecules. It is reduced and incorporated into organic molecules by nitrate reductase, a light-activated enzyme whose activity is genetically controlled.

10.9.1.6 Ammonium Translocation

Ammonium must be rapidly incorporated into organic molecules because free ammonium disorganizes the photosynthetic mechanism by uncoupling redox reactions and affecting the photosynthetic membrane stacks (grana) in chloroplasts.

10.9.1.7 Assimilation

The ammonium (NH_4^+) ion is toxic to plants and must be incorporated into N compounds immediately upon absorption. Conversely, nitrate is not toxic and can be stored in plants until utilized. Regardless of the inorganic form of N absorbed, the ammoniacal form of N is incorporated into alpha-ketoglutarate to yield glutamate in chloroplasts. This reaction is controlled by the glutamate dehydrogenase enzyme.

Other amino groups may be added to glutamate residues to produce glutamine under control of the glutamine synthetase enzyme. The reactions are reductive assimilations ($NADPH + H^+ \rightarrow NADP$) and require energy transfer from ATP. Two glutamate residues may also be formed by transamination of alphaketo-glutarate by glutamine under the control of glutamate synthetase. A series of transaminations using glutamate and glutamine as amino group donors initiates the synthetic pathways of other essential amino acids using the corresponding alpha-keto acids as receptors.

10.9.1.8 Essential Role of Nitrogen Nutrition in Higher Plants

Nitrogen is involved in the structures of all amino acids, proteins, and many enzymes. It is also a component of the puric and pyrimidic bases, and therefore is a constituent of RNA and DNA. Nitrogen is also present in the tetra-pyrrole rings of chlorophyll, NADH, NADPH, choline, and indoleacetic acid. It exists as free nitrate in vacuole sap. It will accumulate at substantial concentrations (>1,000 ppm) in the conductive tissues (petioles and stems) during the vegetative period of growth. Therefore, petioles of certain crops can be used as indicators of N status during the vegetative period.

10.9.1.9 Adequate Range and Nutritional Disorders

10.9.1.9.1 Sufficiency Range

Nitrogen contents in plants range between 1.0 and 6.0% of dry weight in leaf tissues. High N levels, however, can cause growth stimulations that may produce deficiencies of other elements (if not supplied additionally) due to dilution effects. Petiole measurements of nitrate range from 8,000 to 12,000 ppm during early growth to 3,000 to 8,000 ppm mid-season. Nitrate is concentrated primarily at the bases of the main stems and in the petioles of recently matured leaves.

10.9.1.9.2 Deficiency

All N forms are mobile in plants. Therefore, N deficiency symptoms first appear on older leaves. Under N shortage, plants grow slowly and are weak and stunted. Leaves are small, the foliage color is light green to yellow, and older leaves often fall prematurely. Necrosis of leaves or leaf parts occurs at a rather late and severe stage of deficiency. Root growth is reduced and branching is restricted, but root:shoot ratio usually increases. Yield and quality are significantly reduced.

10.9.1.9.3 Toxicity

Plants can tolerate excess nitrate to a much greater degree than excess ammonium. Ammonium levels can be toxic to plants if not incorporated into carbon containing N compounds after absorption. Ammonium can also restrict K uptake by competing for root uptake binding sites. When ammonium is the dominant form of N available for uptake, toxicity conditions may develop. The toxicity of ammonium ions is characterized by restricted root growth, which is often discolored, and results in a break-down of vascular tissue, thereby restricting water uptake.

Foliar symptoms can include chlorosis and necrosis of leaves, epinasty, and stem lesions. However, a small application of an ammonium-based fertilizer at the end of the growing season on leafy vegetables or ornamentals produces a desirable darker green leaf color without reducing growth. With ammonium fertilization, secondary problems, such as K, Ca, and Mg deficiencies, often occur. Fruits may develop blossom end-rot symptoms and poor set.

10.9.1.10 Interactions with Other Elements

Ammonium depresses the uptake of the essential cations such as K, Ca, and Mg, while nitrate depresses the uptake of essential anions (P and S). Chlorine can also compete with nitrate for uptake. Ammonium-fed plants often have higher P contents than nitrate-fed plants due to acidification of the rhizospheres with ammonium absorption and subsequent H^+ ion release. Ammonium applications can reduce Fe deficiencies in calcareous soils. Because the nitrate reductase enzyme requires Mo, a deficiency of Mo reduces the rate of nitrate reduction and thereby decreases N use efficiency.

10.9.2 Phosphorus (P)

The atomic number of phosphorus is 15; its atomic weight is 30.97. Brand discovered it in 1772 and Ville proved it essential to plants in 1860.

10.9.2.1 Phosphorus in Soil

Phosphorus exists in the soil as: (i) calcium phosphate resulting from the weathering of primary P-bearing minerals; (ii) non-labile, or strongly bound P; (iii) organic P in humus and organic residue; and (iv) soluble and adsorbed phosphates which constitute P in solution (0.1 μg P per mL). Of the adsorbed P, only the mononuclear fraction is considered to be in equilibrium with P in solution, and therefore accessible to plants.

10.9.2.2 Soil Dynamics

The pKa values of phosphoric acid are 1, 6, and 12. In the pH range of 5.5 to 7.0, the dominant form is $H_2PO_4^-$, and P availability is highest. Insoluble iron phosphates and aluminum phosphates are formed at low pH, while insoluble calcium phosphates and magnesium phosphates are formed at pHs above 7.0. Phosphorus released from decomposition of plant residues can be a relatively significant source of available P.

Because P is relatively immobile in the soil, banding P 5 to 8 cm to the side and 3 to 5 cm below the seed is preferable to broadcast application. Flooding from rain or excessive irrigation leaches only P in soil solutions, while erosion is the major means of P removal from the soil.

10.9.2.3 Fertilizers

Phosphorus in fertilizer is expressed as phosphate or P_2O_5. The main sources of P are normal superphosphate (0-20-0), triple superphosphate (0-46-0), monoammonium phosphate (MAP, $NH_4H_2PO_4$, 11-48-0), diammonium phosphate [DAP, $(NH_4)_2HPO_4$, 18-46-0], ammonium phosphates, ammoniated superphosphates, and potassium phosphate (KH_2PO_4).

10.9.2.4 Uptake and Assimilation by Higher Plants

10.9.2.4.1 Uptake

Phosphorus reaches root surfaces mainly by diffusion along a concentration gradient. However, P only moves a short distance in the soil and must be placed near roots to achieve absorption. Soil factors such as moisture, buffering capacity, and temperature, and plant factors such as root length, root mass, and intensity of mycorrhizal infection all influence the rate of P uptake by roots.

Phosphorus is taken up actively as $H_2PO_4^-$ and does not undergo redox changes in plants. Phosphorus in root cells and xylem sap has been measured at levels 100 to 1,000 times greater than P in soil.

The absorption of P utilizes a cotransport or antiport system. The cotransport system comprises adenosine triphosphatases (ATPases) that pump H^+ into the apoplasts to protonate a phosphate carrier that crosses the plasmalemma. The pH in the apoplasts controls P uptake. In the antiport system, HCO_3^- is pumped out while $H_2PO_4^-$ is pumped in. For each $H_2PO_4^-$ ion absorbed, the equivalent of one OH^- ion is released into the soil and that tends to increase the rhizosphere pH.

Phosphorus uptake is genetically determined and differs among species and cultivars. The genetic factor is especially important in choosing rootstock materials. Phosphorus uptake is greater in early plant life and decreases with maturity.

10.9.2.4.1 Assimilation

Within minutes of uptake, most P is converted to organic P (mostly hexose phosphates and uridine diphosphate) and is quickly metabolized. Phosphorus is mobile in plants and downward movement occurs mainly in the phloem as either inorganic or organic P (phosphatidylcholine); 85 to 90% of inorganic P may be stored in vacuoles, primarily as orthophosphate.

10.9.2.5 Phosphorus Nutrition in Higher Plants

10.9.2.5.1 Cell Buffer System and Metabolism Regulation

Because phosphoric acid (H_3PO_4) is a tri-acid, its successive dissociations allow P to buffer cell pH and maintain homeostasis. Levels of inorganic P regulate the activities of enzymes such as phosphofructokinase and adenosine diphosphate (ADP) glucose pyrophosphorylase, and are involved in controlling starch synthesis and climacteric respiration during fruit ripening.

10.9.2.5.2 Energy Carrier Function

The breakage of P-P bonds in diphosphate and triphosphate nucleotides (mainly adenosine triphosphate or ATP) and phosphocreatine, all release energy that may be used for biosynthesis or ion uptake. The reduction of nicotinamide adenine dinucleotide phosphate ($NADP^+$) into NADPH also releases energy for use in respiration, glycolysis, and CO_2 fixation.

10.9.2.5.3 Nucleotides

Mono-, di- and triphosphates are constituents of nucleic acids (DNA, tRNA, mRNA, and rRNA). Uridine triphosphate (UTP) is required for sucrose and callose synthesis; cytosine triphosphate (CTP) in phospholipid synthesis; and guanidine triphosphate (GTP) in cellulose formation.

10.9.2.5.4 Energy Reserve and Other Functions

Phytin is the Ca or Mg salt of phytic acid, an ester of inositol. During germination, phytin is hydrolyzed to free inorganic P that is used to form organic compounds for metabolic processes and cell walls. Phosphorus is present in membrane phospholipids (phosphatidyl inositol, phosphatidyl serine, and choline) as a lipid anchor constituent of certain lipoproteins and lipopolysaccharides.

10.9.2.6 Adequate Range and Nutritional Disorders

10.9.2.6.1 Sufficiency Range

Phosphorus concentrations in mature leaves range from 0.2 to 0.5%. Phosphorus content in actively growing plant parts is higher because intense anabolism requires multiple energy transfer reactions involving ATP.

10.9.2.6.2 Deficiency

Phosphorus deficiency generally occurs when the P content of a plant is below 0.2%. Temporary P deficiency can be caused by low soil temperature, especially after early spring planting. This is why P as DAP is often included in the formulations of pop-up fertilizers. Phosphorus deficiency

leads to retarded growth and lower shoot:root ratios. Symptoms include darkish green color in older leaves. Purplish areas and necrosis of leaf margins will appear. Deficiency results in low production of fruits, seeds, and flowers of poor quality.

10.9.2.6.3 Toxicity

Very high P levels in growing media can depress growth, primarily by decreasing the uptake and translocation of Zn, Fe, and Cu. Toxicity occurs when the P level in tissue exceeds 1.00%.

10.9.2.7 Interactions with Other Elements

For many crops, a 10:1 ration of N:P is considered optimum. In alkaline soils, ammonium-based fertilizers increase P availability via their acidifying effects. Increased Ca in solution increases P uptake, possibly because Ca stimulates the transport of P at the mitochondrial membranes. However, all calcium phosphate salts have low solubilities in water at high pH.

Magnesium is an activator of kinase enzymes and activates many reactions involving phosphate transfers. Aluminum can form aluminum phosphates in the intercellular regions of root tips, which restrict P translocation and induces P deficiency. However, Al uptake is often accompanied by increased P uptake, and high root P levels often occur with high Al levels. It is unclear whether the P is available for use by the plants. Iron is believed to interfere with the absorption, translocation, and assimilation of P by forming iron phosphates. High levels of P will induce Zn deficiency symptoms in plants with adequate levels of Zn. Conversely, high levels of Zn have been found to interfere with normal P metabolism.

10.9.3 Potassium (K)

The atomic number of potassium is 15; its atomic weight is 39.10. Davy discovered it in 1807 and von Sachs and Knop proved it essential to plants in 1860.

10.9.3.1 Potassium in Soil

Potassium in soils exists as (1) a structural component of primary and secondary minerals; (2) fixed K in the lattices of clay minerals; (3) adsorbed and exchangeable ions at the surfaces of soil colloids; and (4) solutes of soil solutions. Total K content ranges from 0.5 to 2.5% in most soils; this represents about 20 tons per acre. However, only 0.1 to 2% of total soil K is readily available to plants.

10.9.3.2 Soil Dynamics

The weathering of K-containing feldspars results in the release of K into the soil solution for plant utilization. Potassium may also move back within the interlayers of clay particles and become trapped. Because 1 to 2 g K can be fixed by 100 g of clay minerals, this phenomenon, called K fixation, is of agricultural importance in clay-containing soils.

10.9.3.3 Fertilizers

The main fertilizer sources of K are potassium nitrate (KNO_3), potassium sulfate (K_2SO_4), potassium chloride (KCl) and Sul-Po-Mag (a double salt of potassium and magnesium sulfate).

10.9.3.4 Uptake and Assimilation by Higher Plants

Eighty-five percent of K movement in the soil is by diffusion through the water films around soil particles. Because diffusion is a relatively slow process, K fertilization may be needed to maintain high levels of exchangeable K. Rapid plant growth and uptake may deplete K in the soil around

the root surfaces. At high soil K levels, readily available soil moisture and warm temperatures increase K movement from the soil to the roots and ensure adequate levels to sustain growth.

10.9.3.5 Adequate Range and Nutritional Disorders

10.9.3.5.1 Sufficiency Range

In healthy, recently and fully developed leaves, the typical sufficiency range for K is 1.5 to 4% on a dry weight basis, with a N:K (w:w) ratio of 1:1. Sufficient K can be as high as 6 to 8% in the stem tissues of some vegetable crops. Highest concentrations are found in new leaves, petioles, and stems. High-yielding crops absorb 56 to 560 kg K per ha (50 to 500 lb K per acre), but many species absorb more K than they need; the excess is frequently called "luxury consumption."

10.9.3.5.2 Deficiency

Because K is mobile in plants, deficiency symptoms first appear in older tissues. For most vegetable crops, K deficiency symptoms are usually manifest as a light green to yellow areas around the edges and tips of older leaves. The leaves appear as if they had been burned along the edges, a deficiency symptom known as *scorch*. Deficient plants easily lodge and are sensitive to disease. The production of grain, fruit, and flowers and their quality and shelf life are all reduced when K is deficient.

10.9.3.5.3 Toxicity

Plants with an excess of K will first become deficient in Mg, then Ca, due to induced nutrient element imbalances that upset normal K:Mg and K:Ca ratios if Mg and Ca are at the low ends of their sufficiency ranges.

10.9.3.6 Interactions with Other Elements

Levels of K and N are closely related in most plants. In general, abundant N increases sensitivity to disease infection, while K increases resistance to infection. Nitrogen stimulates rapid, soft growth, while adequate K balances this effect by promoting the growth of firmer tissues. The responses of these elements to applications of either one are often dependent on the levels of the other. Applications of K without sufficient N may lead to decreased N content in young plants. Without sufficient K, N was found to increase in outer cabbage leaves and in tomato upper stems and leaves. In sugarcane sheath tissue, the relationship of K to N is related to the concentration of each, N rising as the percentage of K is raised or lowered beyond 2%, which is its critical value.

The source of N has a bearing on the accumulation of K. At several N levels, an increase of nitrate tends to result in K accumulation, while ammonium tends to depress K concentration. Increasing Ca levels tends to nullify the negative effects of increased N on K uptake. Ammonium has a greater depressing effect on K in soil-grown plants than those grown in solution culture because it interferes with the diffusion of K from the clay lattice and competes with K for uptake.

Potassium also influences the uptake and/or utilization of the two forms of N. The uptake of nitrate is affected by K, a factor thought to be one of the essential functions of K. For most vegetable crops, larger amounts of ammonium (NH_4) can be used without causing toxicity as the amount of K is increased in the tissue. This suggests an optimum NH_4:K ratio for growth. In tomato, occurrence of stem lesions increases as the NH_4:K ratio in the substrate exceeds 1:4.

The relative presences of K, Ca, and Mg influence the concentration of each individual cation within the plant. Potassium seems to be the most active. It exerts a greater depressing effect on Ca and Mg than Ca and Mg exert on K. Magnesium has a greater depressing effect on K plant content than on Ca content. Calcium appears to be less antagonistic to Mg than to K. Evidently, a strong mutual antagonism exists between K and Ca, since high concentrations of both these elements seldom exist simultaneously.

While the K:(Ca + Mg) ratio in plant tissue tends to be constant, variations are caused by the source of N, stage of growth, lime additions, and deficiencies of Mg or K. The use of nitrate favors cation uptake, although sodium nitrate can depress Ca uptake. Cation content also tends to increase with age if low levels of K are present. Total cation amounts also tend to increase as lime is added, possibly due to replacement of the H^+ cation on the exchange complex with mostly Ca when high-Ca content lime is applied or when both Ca and Mg are increased if dolomitic limestone is the liming material. Total equivalents of cations tend to decrease if either K or Mg is deficient.

Despite the interrelationships between K and Ca + Mg in plant tissue, critical values of these elements are usually not seriously affected unless the ratio of one of these elements to another is very wide. In corn, for instance, a K:Mg ratio of 10:1 or less in the ear leaf is satisfactory, but a 14:1 ratio can lead to serious growth restriction, although both may contain more than the critical concentration of 0.3% Mg.

Because K and Na ions are similar in ionic size and chemical properties, Na may replace K in several of essential roles, but K is an essential element and Na is not. Therefore, Na applications may reduce the effect of K shortage, but will not produce healthy plants when K is deficient. The extent of this substitution is dependent on plant species and the amount of K present.

Sodium-for-K substitution can be substantial in plants such as sugar and table beets, spinach, turnip, and Swiss chard, but only if the level of available K is low. Substitution is small or absent in plants such as barley, buckwheat, corn, flax, millet, rape, rye, soybean, and wheat. The substitution of K by Na may make the interpretation of K status difficult for some plants. In the case of sugar beets, for example, this problem can be avoided by using the leaves rather than the petioles for K diagnosis.

Under saline conditions, Na concentrations in several tropical and temperate crops may be reduced by applications of potassium chloride.

10.9.4 Calcium (Ca)

The atomic number of calcium is 20; its atomic weight is 40.08. Davy discovered it in 1807 and von Sachs and Knop proved it essential to plants in 1860.

10.9.4.1 Calcium in Soil

Calcium is present in various soil minerals including phosphates (apatite), silicates, sulfates (gypsum), and carbonates (calcite and dolomite). Weathering of these minerals releases Ca^{2+} ions that may be adsorbed onto organic and inorganic soil colloids, thus contributing to clay flocculation, particle aggregation, and soil structure. Calcium adsorbed on the surfaces of soil colloids and in soil solutions is available for plants.

10.9.4.2 Fertilizers

The primary sources of Ca are liming materials such as calcite, dolomite, hydrated lime, precipitated lime, and blast furnace slag. Although Ca is often called a base or basic cation, the increase in soil pH after liming comes from reactions involving carbonates and carbonic acid, and not from Ca alone. Other Ca sources have limited effects on soil pH; they include gypsum, calcium nitrate, and calcium chloride.

10.9.4.3 Uptake and Assimilation by Higher Plants

Calcium moves in the soil mainly by mass flow. Uptake is passive and restricted to the tips of young roots where the walls of the endodermis cells are still unsuberized. Calcium uptake is reduced when root tips are damaged by nematodes or chemically altered by ions such as NH_4, Na, or Al. Calcium uptake is also depressed by competitive uptake with ammonium and K. Water stress can also depress Ca uptake by damaging root tips.

10.9.4.4 Translocation and Assimilation

Calcium is translocated in the xylem mainly through the transpiration stream. Upward movement in the xylem is also facilitated by exchange sites where Ca^{2+} is momentarily adsorbed and by chelation with organic acids of the xylem sap. The higher the concentration of Ca in the xylem sap, the faster it moves through the plant, preferentially toward the shoot apices of growing plants. Calcium is also transported in the phloem in very small amounts. Thus, Ca levels in plant organs largely provided through the phloem are rather low, with downward Ca movement limited. High relative humidity can reduce Ca movement to meristematic tissue, creating a Ca deficiency in the growing tips of plant tissues.

10.9.4.5 Nutrition in Higher Plants

Most of the Ca present in cells is located in the apoplasts and vacuoles, while cytoplasmic concentrations are low. The main structural role occurs in the middle lamella between adjacent cell walls, where Ca binds with free carboxyl groups of pectines. It acts as a cement between adjacent cell walls. Ca is also involved in cell elongation in the shoots and growing tips of roots.

The removal of Ca from the cell walls is part of the leaf abscission and fruit ripening processes. Applications of Ca to senescing leaves reduce the catabolytic effects of cytokinins. Therefore, post-harvest quality and rates of decay of flowers, foliage, fruits, and vegetables are dependent on Ca levels. Calcium is also involved in the expression of chilling-injury symptoms during cold storage.

Calcium in vacuoles may form insoluble crystals of oxalate, carbonate, sulfate, or phosphate, thus regulating the levels of these anions at toxic levels. In the cytoplasm, the Ca–calmodulin complex can allosterically activate enzymes such as cyclic nucleotide phosphodiesterase, adenylate cyclase, membrane bound Ca^{2+}-ATPase, and MAD-kinase. Calcium alone is believed to directly activate mitochondrial enzymes such as glutamate dehydrogenase and several u-amylases involved in starch degradation in the chloroplasts. Calcium also stabilizes the mitotic spindle apparatus during cell division, and enhances pollen tube growth and germination. Accumulation of callose in the germination tube helps the movement of the pollen into the female cells.

10.9.4.6 Adequate Range and Nutritional Disorders

10.9.4.6.1 Sufficiency Range

Adequate levels of Ca in mature leaves range from 0.5 to 1.5%. About 800 ppm (0.08%) is considered chemically active. Higher levels are required to counter the effects of other ions and their negative effects on plant metabolism.

10.9.4.6.2 Deficiency

Calcium deficiency is characterized by a reduction in the growth of meristematic tissues. The deficiency occurs first in the growing tips and youngest leaves because Ca is immobile in plants. Calcium-deficient leaves become deformed and chlorotic; in later stages, their margins become necrotic. Temporary deficiencies may occur when Ca levels in the xylem drop because of reduced transpiration on humid, cloudy days or during water shortages. A shortage of Ca to growing and transpiring fruits results in bitter pits of apples, tip burn, and brownheart of leafy and heading vegetables, blossom-end rot of tomato, squash, watermelon, and bell pepper, and asparagus tip deterioration. Blossom-end rot is an irreversible disorder. Exogenous applications of Ca may be used as preventive measures but will not correct existing symptoms.

10.9.4.6.3 Toxicity

Symptoms of excess Ca in vegetables are uncommon, but appear mainly as Mg- or K-induced deficiencies.

10.9.4.7 Interactions with Other Elements

Calcium uptake is affected in decreasing order by the presence of ammonium, Mg, K, and Na. Foliar Ca:Mg ratios of 2:1 and K:Ca of 4:1 are considered optimum for growth. Nitrate usually increases Ca uptake, possibly by the formation of Ca–organic acid chelates released during nitrate uptake. In acid conditions, P favors Ca uptake. The formation of low solubility calcium phosphates in soils with pH >7.0 reduces Ca availability.

Increases in pH after excessive liming results in induced Fe, Mn, B, or Zn deficiencies and subsequent chlorosis. In soils at pH <5.0, Ca may bind with Al and Fe hydroxides. In cells, Al toxicity is due to the competition between Al and Ca for binding sites on calmodulin. Calcium uptake by roots is restricted due to competition with Al for root uptake binding sites. Calcium and B exert synergistic effects in reducing the incidence of disorders near actively growing points

10.9.5 Magnesium (Mg)

The atomic number of magnesium is 12; its atomic weight is 24.31. Davy discovered it in 1808 and von Sachs and Knop proved it essential to plants in 1860.

10.9.5.1 Magnesium in Soil

Magnesium exists in the soil (1) in primary ferromagnesium minerals such as biotite, hornblende, olivine, or serpentine; (2) in secondary clay minerals such as chlorite, illite, vermiculite, or montmorillonite; and (3) in inorganic salts such as carbonates, sulfates, or dolomite. Magnesium is seldom associated with the organic matter complex. Magnesium in primary and secondary minerals is nonexchangeable. Exchangeable Mg adsorbed onto the surfaces of soil colloids and soluble Mg in soil solutions are available to plants over the 5.4 to 7.0 pH range.

Isomorphous substitution between iron (Fe^{3+}) or aluminum (Al^{3+}) and magnesium (Mg^{2+}) ions produces positive charges on surfaces of clay minerals. Low soil pH favors weathering of ferromagnesium minerals, resulting in the release of Mg. Exchangeable Mg represents approximately 5% of the total in soil. Magnesium levels in highly leached or sandy soils are usually low. Tropical soils are generally low in Mg and require Mg fertilizer for proper growth.

10.9.5.2 Fertilizers

Magnesium is found in liming materials primarily as dolomitic limestone. The rise in soil pH induced by these liming materials comes from reactions involving carbonates and carbonic acid, not Mg. Particle size of Mg-containing liming materials affects Mg availability as these materials have relatively low solubilities. Finely ground dolomitic limestone changes soil pH faster than coarse material. Under intensive cropping systems, Mg availability may be limited to the second or third crop. Reduced Mg availability is due to slow rate of release, not to low Mg levels. Dependency on Mg release from dolomitic lime is not adequate to support intense cropping systems and necessitates supplemental Mg fertilizer during the growth cycle. Applications of Mg in its nitrate, chloride, or sulfate forms are common and have little effect on soil pH.

10.9.5.3 Magnesium Uptake and Assimilation by Higher Plants

Magnesium moves to the roots by mass flow. Uptake is passive, possibly mediated by ionophores in which Mg^{2+} moves down an electrochemical gradient. The involvement of ionophores may explain the effect of cation competition (NH_4, K, Ca, and Na) on Mg uptake.

10.9.5.4 Translocation and Assimilation

Magnesium is mobile in the phloem and can be transported from older to younger leaves or to the shoot apices. Because fruit and storage tissues depend on the phloem for their mineral supplies, they are higher in K and Mg than in Ca. In some cases, bitter pits may be due to a localized Mg toxicity rather than a Ca deficiency.

10.9.5.5 Nutrition in Higher Plants

Magnesium found in the centers of the tetrapyrrole rings of chlorophyll molecules comprises 15 to 20% of the total Mg in plants. Another 70% is associated with anions and organic anions, malate, and citrate. Magnesium is a cofactor of kinase enzymes such as hexokinase and phosphofructokinase, which require divalent cations such as Mg^{2+} or Mn^{2+} for activity. These enzymes catalyze the transfer of phosphoryl groups between ATP and ADP.

Magnesium is essential for the activities of the two principal CO_2-fixing enzymes, ribulose phosphate carboxylase and phosphoenolpyruvate carboxylase. It activates ribulose phosphate carboxylase in the light reactions of photosynthesis in chloroplasts. Light triggers the import of Mg^{2+} into the stroma of the chloroplasts in exchange for H^+ ions that provide optimum conditions for the carboxylase reaction.

With its two positive charges, Mg also stabilizes the tails of phosphoryl groups in ATP and ADP by weakly binding with negative charges. Magnesium is the most important cation neutralizing the nondiffusible anions of the thylakoid membrane. It also stabilizes the ribosomes in adequate configuration for protein synthesis.

10.9.5.6 Adequate Range and Nutritional Disorders

10.9.5.6.1 Sufficiency Range

The normal concentration of Mg in plants ranges from 0.15 to 0.40%.

10.9.5.6.2 Deficiency

Because Mg is relatively mobile in plants, deficiency symptoms develop first in older leaves. Magnesium deficiency is characterized by interveinal yellowing of the leaf blades that progresses from the edges to the centers. The most typical pattern of Mg deficiency is green conductive tissue surrounded by yellow background. Ultimately, leaves become stiff and brittle and the veins become twisted. Mg uptake is strongly influenced by pH, its availability markedly declining when the soil pH is below 5.5.

10.9.5.6.3 Toxicity

In field conditions, Mg toxicity rarely occurs.

10.9.5.7 Interactions with Other Elements

Magnesium uptake is affected in decreasing order by K, NH_4, Ca, and Na. Foliar Ca:Mg ratios of 2:1 and K:Mg of 8:1 are considered optimum for growth. Mg depresses Mn uptake. In acidic soils, Al competes with Mg for uptake at root uptake binding sites. Aluminum-induced Mg deficiency has been implicated in acid rain-induced forest declines in Europe and in tropical soils fertilized with ammonium-based fertilizers.

10.9.6 Sulfur (S)

The atomic number of sulfur is 16; its atomic weight is 32.06. Sulfur was known in ancient times; von Sachs and Knop proved it essential to plants in 1865.

10.9.6.1 Sulfur in Soil

Over 90% of available S in soil is found in association with organic matter, which has a 10:1 N:S ratio. Soil organic S is found in protein and amino acids, and may be associated with Fe and Al oxides, clay minerals, or soil humus fractions.

In well drained soils, inorganic S exists as: (1) soluble sulfates (SO_4^{2-}) of Ca, Mg, K. Na, or NH_4; (2) sulfate adsorbed on clay surfaces; (3) sulfate adsorbed to Al or Fe hydrous oxides at pH <4.0; and (4) sulfates coprecipitated with natural calcium carbonates at pH >7. Most available sulfate is found at lower depths, where pH and base saturation are lower and exchangeable Al is higher. The availability of subsoil sulfate for growth depends on the crop rooting habits and on soil water movement.

10.9.6.2 Soil Dynamics

Sulfur in soil is made available to plants from S-containing rainfall, fertilizer application, or microbial activity. Volcanic eruptions and burning of fossil fuels by automobiles and factories liberate S into the air. Rainfall then deposits it on soils. This phenomenon, called acid rain, may annually return to the soil up to 50 kg S per ha (44.6 lbs per acre).

Under aerobic conditions, soil microorganisms mineralize S containing amino acids such as cysteine into sulfate, which annually releases approximately 4 to 13 kg S per ha (3.6 to 11.6 lbs per acre). In anaerobic conditions, mineralization and sulfate reduction by *Desulfovitorio* may produce hydrogen sulfide (H_2S) that can be released into the atmosphere. In waterlogged soils, the degradation of organic matter releases organic sulfides such as methyl and butyl sulfides. Hydrogen sulfide may be oxidized to elemental S by chemotrophic S bacteria. When aerobic conditions are restored, H_2S readily undergoes autoxidation to sulfate.

Photosynthetic green and purple bacteria can oxidize H_2S to S by utilizing H^+ for photosynthetic electron transport. When this process is restricted, hydrogen sulfide may accumulate to toxic levels and thus impair plant growth.

Sulfur may be removed from soil by leaching or crop uptake, or can be lost as various gases. Sulfates adsorbed to AlOH or FeOH groups may be displaced by the electrostatic effects of excess cations or by phosphates that are more strongly adsorbed to Al and Fe oxides than are sulfates. Sulfate adsorption decreases with increasing pH, and is negligible above 6.5. The desorbed sulfate is relatively mobile in soils and may then be taken up by plants or leached. Increases in soil acidity or in amounts of Fe and Al hydroxides reduce sulfate leaching. Although plants remove almost as much S as P, larger amounts of S are lost from the growing zone through leaching, erosion, and decomposition as compared to P.

10.9.6.3 Fertilizers

Sulfur is frequently applied as a sulfate fertilizer element because S is the accompanying anion in ammonium sulfate (24% S), magnesium sulfate (13% S), potassium sulfate (17.5% S), and calcium sulfate (18.6% S). Sulfur is also present in superphosphates since sulfuric acid is used to acidulate phosphate rock and convert P into a soluble form in the manufacture of superphosphate fertilizers.

10.9.6.4 Uptake and Assimilation by Higher Plants

Elemental S is also available as a yellow powder that, upon addition to the soil, liberates dilute sulfuric acid and lowers soil pH. An application of 1 kg S per ha (0.89 lbs per acre) lowers the pH approximately 0.5 unit.

Mass flow moves sulfates to the roots, which makes uptake dependent on soil moisture. Concentrations of 3 to 5 mg S per liter in soil solutions are adequate for most plant species. Once at the root surfaces, sulfate (SO_4^{2-}) ions are actively absorbed against an electrochemical gradient. Generally, soil

pH and other nutrient elements have little influence on sulfate absorption. Sulfur may be absorbed through the stomata as SO_2 at atmospheric concentrations between 0.5 to 0.7 mg SO_2 per m^3.

The N:S ratio in the growing medium may be as important as total S alone, or the ratio of sulfate S to total S. An adequate N:S ratio for most plants species is 15:1; for crucifers, 3:1; for legumes, 13:1; and for cereals, 17:1. For most crops, S uptake is similar to that of P, and ranges from 10 kg S per ha in cereals and grasses to 45 kg S per ha in crucifers.

After uptake, sulfate is translocated to shoots in the xylem, may be reduced to sulfite, and is immobilized. Little downward movement occurs in the phloem. Sulfur moves in the phloem mainly in the reduced SH (thio) form. During shortage, sulfate is redistributed from roots and petioles to younger tissues. Older leaves do not contribute significantly to S supplies for younger tissues. Sulfate must be reduced before it is incorporated into the cysteine, cystine, or methionine amino acids. Sulfate reduction is most prominent in chloroplast membranes of green tissues, especially in daylight hours.

10.9.6.5 Nutrition in Higher Plants

Several essential functions are attributed to S. Disulfide bonds are formed by two SH groups of cysteine or methionine. These bonds are involved in the tertiary structures of proteins. Sulfur is involved in the conformations and activities of many enzymes.

Sulfur is also essential for the formation of glucoside oils and volatile compounds found in plants in the onion and garlic families. It promotes legume nodule formation and stimulates seed production. It also helps plants withstand low temperatures.

One of the most important S-containing proteins is ferredoxin, which is involved in CO_2 assimilation, glucose synthesis, glutamate synthesis, N_2 fixation, and NO_3 reduction. Sulfur is also a constituent of coenzyme A, biotin, and thiamine. CoA is a coupling substance in the Krebs (citric acid) cycle and is important in lipid and fatty acid metabolism. Biotin is associated with carbon dioxide assimilation and decarboxylation. Thiamine acts as a coenzyme in the decarboxylation of pyruvate and oxidation of u-keto acids. Sulfur is also a component of glutathione and various plant hormones.

10.9.6.6 Adequate Range and Nutritional Disorders

10.9.6.6.1 Sufficiency Range

Sulfur content in leaf tissues ranges from 0.15 to 0.50% on a dry weight basis. Symptoms of S deficiency may occur in newly emerging plants and tend to disappear with root development.

10.9.6.6.2 Deficiency

The main causes for S deficiencies in cultivated crops are low S or high N levels in the soil, sulfate leaching, or inadequate water regime. Sulfur deficiencies are corrected easily by soil applications of S-containing fertilizers.

Because S is associated with the formation of proteins and chlorophyll, its deficiency symptoms resemble those of N deficiency. Unlike N, S is not highly mobile in plants, so S deficiency symptoms first appear on younger leaves. Initially, S-deficient plants are light yellow-green. Red or purple pigmentation may appear later. Fruits are light green and lack succulence. Roots are longer than normal, and stems become woody. The most typical symptoms of S deficiency are stunted chlorotic growth and short, thin, woody stems. Leaf area and fruit set are reduced. In legumes, root nodulation is reduced; in grain crops, maturity is delayed. In tobacco, S deficiency is needed to produce proper leaf color and burning quality.

10.9.6.6.3 Toxicity

Plants are relatively insensitive to high sulfate (SO_4) concentrations in growing media. Although acute sulfur dioxide (SO_2) damage is common, its occurrence is usually localized near the source and is related to weather conditions favoring slow dispersion of the gas. Toxicities are more common

when atmospheric concentration exceeds 0.5 to 0.7 mg SO_2 per m^3 and are generally described as water-soaked areas on the leaves that develop into well-defined dry, white necrotic spots, mainly on the undersides.

At cellular level, chloroplast membranes are disrupted by excess sulfate. These toxicity symptoms may resemble N deficiency, but younger leaves will be chlorotic and foliar analysis is likely to reveal a high nitrate content due to effects of S on ferredoxin. Another internal disorder is inhibition of protein synthesis accomplished by an increase in non-S-containing amino acids such as asparagine, glutamine, and arginine. A reduction in photosynthesis is associated with low sugar and high amide N levels.

10.9.6.7 Interactions with Other Elements

Sulfur is synergistic with N and F and is antagonistic to As, B, Mo, Pb, Se, and Fe. Sulfur and N in plants have a close relationship. Field crops require an average S:N (w:w) ratio of 1:15 for protein synthesis, ranging from 1:14 for grasses to 1:17 for legumes. Generally, additions of S will increase the N content but the degree of increase can vary with the age of the tissue. Although the S:N ratios of specific proteins are constant, they will vary at each stage of growth and among plant species. Unlike total N, plant nitrate tends to increase as S becomes limiting. The S concentration in plant proteins, which ranges from 0.5 to 3.0%, is probably responsible for the relationship of S and P because some proteins contain P.

10.10 SUMMARY: PLANT NUTRITION AND ESSENTIAL MICRONUTRIENTS

10.10.1 Boron (B)

The atomic number of boron is 5; its atomic weight is 10.82. Gay-Lussac and Thenard discovered it in 1808 and Sommer and Lipman proved it essential to plants in 1926.

10.10.1.2 Boron in Soil

Total B content in soils ranges from 20 to 2,000 mg per kg (ppm); available B ranges from 0.4 to 5.0 ppm. Boron is found in primary minerals such as borax ($Na_2B_4O_7{\cdot}10H_2O$), kermite ($Na_2B_4O_7{\cdot}4H_2O$), colemanite ($Ca_2B_6O_{11}{\cdot}5H_2O$), ulexite ($NaCaB_5O_9{\cdot}8H_2O$), kotonite [$Mg_3(BO_3)_2$], and ludwigite ($Mg_2FeBO_3$). Boron may also bind with organic matter or with carbohydrates released during humification. In most agricultural soils, B associated with humic colloids is the principal B pool for plant growth.

As B-containing rocks weather, B is released into the soil solution in the nonionized boric acid (H_3BO_3) form that allows B to be leached easily from the soil. Liming may decrease B availability through the action of Ca and the subsequent rise in pH. At pH above 9.2, the dominant form of B is $B(OH)_4^-$. In this form, B may be adsorbed by sesquioxides and clay minerals, especially Fe and Al oxides.

10.10.1.3 Fertilizers

The most common source of B is borax ($Na_2B_4O_7{\cdot}10H_2O$, 11% B). Other sources include sodium pentaborate ($Na_2B_{10}O_{16}{\cdot}10H_2O$, 18% B), Solubor ($Na_2B_4O_7{\cdot}5H_2O$ and $Na_2B_{10}O_{16}{\cdot}10H_2O$, 20% B), boric acid ($H_3BO_3$, 17% B), colemanite ($Ca_2B_6O_{11}{\cdot}5H_2O$, 10% B), and B frits (2 to 6% B). Trace B is also found in borated superphosphates.

Banding is usually more effective than broadcasting B fertilizers. Application rates from 0.6 to 1.2 kg B per ha are used with most crops and may be increased from 1.2 to 3.2 kg B per ha for

legumes or sugar beets. Optimum rates of B application depend on cultural practices, rainfall, liming, and soil organic matter content.

Boron may be applied via foliar sprays, especially when soils may fix B or when high H reduces availability. Borax and Solubor are the most commonly used sources of B in foliar sprays at rates from 0.5 to 1.5 kg B per ha.

10.10.1.4 Uptake and Assimilation by Higher Plants

Most B enters the roots passively with the transpiration stream as undissociated boric acid. However, small amounts are taken up actively. Factors reducing transpiration, such as high relative humidity or drought, reduce B uptake and translocation. Once within the root-free spaces, B may associate with polysaccharides, remain free as surface film B, or become bound onto cell walls. Boron moves primarily in the xylem as a sugar borate complex. Its movement in the phloem is limited; B is relatively immobile within plants and may be lost through guttation from hydathodes.

10.10.1.5 Nutrition in Higher Plants

Boron functions in plants are related to meristematic growth. Boron is directly involved in cell differentiation, maturation, division, and elongation. The molecular basis of this function arises because B is necessary for the synthesis of uracil, a component of RNA and a precursor of uridine diphosphate glucose. When B levels are limiting, cell division rates are reduced and the number of undifferentiated cells increases.

Boron also affects the growth of pollen tubes, possibly by increasing sugar absorption and metabolism and respiration. Thus, B also exerts indirect control on germination.

Several other roles are attributed to B. It may form complexes with polyhydroxy substrates, enzymes, and coenzymes to stimulate or inhibit metabolic pathways and protect indoleacetic acid oxidase by forming complexes with its inhibitors. Boron may combine with phosphogluconate to block the pentose–phosphate pathway so that glycolysis is favored and phenols do not accumulate. Boron is involved also in the biosynthesis of lignin and differentiation of xylem vessels.

10.10.1.6 Adequate Range and Nutritional Disorders

10.10.1.6.1 Sufficiency Range

The average B content in most plants is 20 mg B per kg (ppm) on a dry weight basis. Boron is unevenly distributed within plants and the highest levels are found in reproductive structures such as anthers, stigmas, and ovaries (sometimes at levels twice those in stems). Most B in leaves accumulates in margins and tips, at levels 5 to 10 times higher than those found in blades.

Boron requirements vary with plant type; in monocotyledon species, leaf content ranges from 1 to 6 ppm; in most dicotyledons, from 20 to 70 ppm; and in dicotyledons with latex systems, from 80 to 100 ppm. Crops such as sugar beet, celery, apple, pear, and grape have higher B requirements. *Brassica* crops such as turnips, cauliflowers, cabbages, brussels sprouts, and some legumes, also have high B requirements.

10.10.1.6.2 Deficiency

Boron deficiency is the most common and widespread micronutrient problem. It is characterized by abnormal or retarded elongation of growing points and/or apical meristems. Young leaves are misshapen, wrinkled, thick, and dark. Terminal growing points die. Leaves and stems become brittle due to effects on cell wall formation or phenol accumulation. Accumulations of auxins and phenols induce necrosis of leaves and other parts. Roots are slimy, thick, bumpy, and have necrotic tips.

Boron deficiency is responsible for crown and heart rot in sugar beet. Young leaves are stunted and brown or black; growing points die and the crowns rot. In turnip, B deficiency causes hollow,

cracked roots with glassy appearances. It causes cracked roots in celery. Fruits of B-deficient plants may be small, misshapen, and of poor quality. Corky material forms in B-deficient apple fruit and tomato plants.

10.10.1.6.3 Toxicity

The range between adequate and toxic levels of B is narrow. Boron-sensitive species include peaches, grapes, figs, and kidney beans. In arid areas, B may accumulate in topsoil layers due to high levels in irrigation water. Levels above 5 ppm in water are toxic for most plants. Above 10 ppm, toxicity may become visible on tolerant plants. Symptoms of toxicity are leaf tip chlorosis and necrosis, and eventually scorch and burn of leaves. Leaves drop prematurely.

10.10.1.7 Interactions with Other Essential Elements

Low levels of B affect phosphate incorporation into nucleic acids and reduce levels of other P-containing compounds such as ATP. The adsorption of P at the roots of B-deficient plants may be reduced by half. High levels of K have been found to decrease B content. Increasing K decreases the calcium:boron ratio. Boron and Ca must be in balance for proper growth. For soybeans, the correct ratio is 500:1. For sugar beets, the ratio should be 100:1. Spraying apples with B has been effective in reducing bitter pit, a disorder related to Ca deficiency. Calcium added to soil helps decrease the incidence of B toxicity. Calcium inhibition of B uptake is especially marked in high pH soils.

10.10.2 Chlorine (Cl)

The atomic number of chlorine is 17; its atomic weight is 35.453. Scheele discovered it in 1774 and Broyer et al. proved it essential to plants in 1954.

10.10.2.1 Chlorine in Soil

Chlorine is present in soil in primary minerals such chlorapatite [$Ca_5(PO_4)Cl$], carnallite ($KMgCl_3 \cdot 6H_2O$), sodalite ($Na_4Al_3Si_3O_{12}Cl$) halite (NaCl) and sylvinite (KCl). Upon weathering of these minerals, Cl^- is released and remains in the soil solution. Chloride (Cl^-) is not adsorbed by soil colloids because of its negative charge. It is leached readily in most soils, and is the most common counterion for Na. Chlorine may be carried by wind to return to the soil. It may also accumulate when saline water is used for irrigation. Chlorine is present in KCl, NH_4Cl, and $CaCl_2$.

10.10.2.2 Uptake and Assimilation by Higher Plants

Chloride in soil follows water movements and is taken up as the Cl^- anion. The greater the Cl concentration in soil solution, the greater its uptake. Chloride is taken up against an electrochemical gradient mediated by a protein carrier. It may also be taken up by aerial parts as Cl^- anion or chlorine gas (Cl_2). Chloride is very mobile in plants.

Chlorine was the last element for which essentiality was established (1954). It is required in the splitting of water (Hill reaction) during photosynthesis and enhances the evolution of oxygen (O_2) and photophosphorylation. It also functions in the transfer of electrons from hydroxyl ions (OH^-) to chlorophyll b in Photosystem II.

10.10.2.3 Adequate Range and Nutritional Disorders

10.10.2.3.1 Sufficiency Range

Chlorine levels from 50 to 200 mg Cl per kg (ppm) are common in plants. Levels are usually highest in leaf blades, followed by petioles, shoots, stems, and fruits.

10.10.2.3.2 Deficiency

Chlorine deficiencies are fairly rare in natural conditions, although deficiencies are related to various fungus and root diseases in small grains, primarily wheat and oats.

10.10.2.3.3 Toxicity

For sensitive crops, toxicity occurs at foliar levels from 0.5 to 2%. Halophytes may contain up to 4% Cl. Toxicity involves premature yellowing and burning of the leaf tips and margins. In severe cases, the leaves are bleached and necrotic in the interveinal areas, margins are scorched, and the leaves abscise. Chloride toxicity under saline conditions is due to chemical effects of large quantities of Cl^- ions to detrimental competition with other essential anions such as nitrate (NO_3^-) and sulfate (SO_4^{2-}), and to induced water stress due to increased water potential in the growing environment.

10.10.2.4 Interactions with Other Essential Elements

Chloride influences NO_3 uptake by competing for exchange sites on soil colloids.

10.10.3 Copper (Cu)

The atomic number of copper is 29; its atomic weight is 63.54. Copper was known in ancient times. Sommer, Lipman, and MacKinnon proved it essential to plants in 1931.

10.10.3.1 Copper in Soil

Most Cu in soils is insoluble and immobile between soil layers due to its binding strength. Liming and raising the pH generally decreases availability, possibly by strengthening the adsorption of Cu^{2+} or $Cu(OH)^+$. Available Cu in soils is most likely present as adsorbed Cu^{2+} that can directly bind carboxylic, carbonyl, or phenolic groups of organic matter in the soil. Complexed and soluble Cu^{2+} are found in the soil solution.

10.10.3.2 Soil Fertilizers

Materials for soil and foliar applications of Cu include copper sulfates ($CuSO_4 \cdot 5H_2O$, 25% Cu or $CuSO_4 \cdot H_2O$, 35% Cu), basic copper sulfates [$CuSO_4 \cdot 3Cu(OH)_2$, 13 to 53% Cu], copper carbonates [$CuCO_3 \cdot Cu(OH)_2$, 57% Cu or $CuCO_3 \cdot Cu(OH)_2$, 55% Cu], copper oxides (Cu_2O, 89% Cu or CuO, 75% Cu), and copper chelates (CuEDTA, CuHEDTA). Soil applications, generally as $CuSO_4 \cdot 5H_2O$, consist of a single application of 1 to 10 kg Cu per ha every few years. Foliar applications of $CuSO_4$ or Cu chelates at rates of 0.3 to 1 kg Cu per ha (0.27 to 0.90 lb Cu per acre) are also common. The Bordeaux mixture of copper sulfate and lime has been long used as a fungicide for grapes and other crops.

10.10.3.3 Uptake and Assimilation by Higher Plants

Copper uptake is active and metabolically controlled. Although roots have the ability to absorb Cu^{2+}, the uptake of chelated Cu also occurs. Copper moves in the xylem via complexing with soluble N compounds such as amino acids. It is not mobile in plants. Approximately half the active Cu in plants is found in the chloroplasts. Concentration in shoots is highest when plants are young and decreases steadily as they mature. Most Cu in flowers is found in anthers and ovaries.

10.10.3.4 Nutrition in Higher Plants

Copper is a component of several enzyme complexes that influence plant carbohydrate and N metabolism. Plastocyanin is a Cu-containing enzyme involved in the electron transport chain of Photosystem I. More than half the foliar Cu is associated with plastocyanin. In the mitochondria,

Cu-containing cytochrome oxidases are components of the respiratory pathway. Other Cu-containing enzymes are involved in oxidation reactions, reducing oxygen to hydrogen peroxide or water. In thylakoid membranes and mitochondria, phenolases catalyze the oxygenation of phenols, which are then oxidized to quinones. Phenolase and lactase are involved in lignin synthesis.

In chloroplasts, the three isoenzymes of superoxide dismutase prevent superoxide (O_2^-) damage by reduction to H_2O_2. This enzyme also contains Zn atoms. In the cytoplasm and cell walls, ascorbic acid oxidase catalyzes the oxidation of ascorbic acid to L-dehydroascorbate and amine oxidases catalyze the oxidative deamination of ammonium (NH_4)-containing compounds, including polyamines.

10.10.3.5 Adequate Range and Nutritional Disorders

10.10.3.5.1 Sufficiency Range

Copper content in most plants ranges from 2 to 20 mg Cu per kg (ppm). The sufficiency range in leaves is 3 to 7 ppm. Copper levels as high as 200 ppm can be found when Cu fungicides are used during crop production.

10.10.3.5.2 Deficiency

Since Cu is immobile, young organs are the first plant parts to show deficiency symptoms. Effects consist of reduced or stunted growth with distortion of young leaves and growing points and necrosis of apical meristems. In chrysanthemums, lateral buds may be distorted or fail to form. Young leaves may have white or bleached tips. This occurs typically in cereals, along with reduced growth and panicle formation. Copper deficiency increases the incidence of lodging, especially when simultaneous growth occurs as a response to N fertilization. Flowering and fruiting may be affected or absent, since pollen and ovaries are very sensitive to Cu deficiency.

10.10.3.5.3 Toxicity

Excess Cu can induce typical Fe deficiencies. Root growth may be stunted, with little lateral root formation, possibly due to membrane damage by excess Cu. Legumes are generally more sensitive to high Cu levels than other plants. Low pH, particularly in subsoil, may restrict root growth.

10.10.3.6 Interactions with Other Essential Elements

High levels of N increase requirements for Cu since it is bound to amino acids. Increased need for Cu may also be related to the dilution effect caused by plant growth. In citrus, heavy or prolonged use of P fertilizers induces Cu deficiencies. Potassium-containing foliar sprays on pecans reduced levels of foliar Cu. In citrus and lettuce, high Cu levels induced Fe chlorosis.

Copper significantly inhibits the uptake of Zn, and vice versa. Zinc is believed to interfere with Cu at the absorption site. Copper may stimulate the uptake of Mn. It also interferes with the role of Mo in the enzymatic reduction of nitrate. A mutual antagonism has been found between Cu and Mo in some plants. If one element is in excess, application of the other alleviated negative symptoms. Aluminum adversely affects Cu uptake.

10.10.4 Iron (Fe)

The atomic number of iron is 26; its atomic weight is 55.85. Iron has been known since ancient times and von Sachs and Knop proved it essential to plants in 1860.

10.10.4.1 Iron in Soil

Iron is present in large amounts (up to 5% of soil) in primary minerals such as ferromagnesium silicates (olivine, augite, hornblende, and biotite) and oxides (hematite and magnetite), but little correlation exists between total and available Fe in soil. As weathering of primary mineral occurs,

Fe appears in clay minerals and may accumulate as hydrous oxides. Iron chemistry in the soil is complex, and depends largely on pH and redox potential. Soluble inorganic forms include Fe^{3+}, $Fe(OH)^{2+}$, and Fe^{2+}. Ferrous iron (Fe^{2+}) is stable as long as low pH and nonoxidizing conditions prevail. However, in the solutions of well aerated soils, Fe^{3+} is the dominant form.

10.10.4.2 Fertilizers

Most Fe deficiencies are due to reduced availability in an unfavorable pH range, not to low Fe levels. The mobility of soluble Fe does not exceed 1.5 cm. Hence, foliar fertilization with ferrous sulfate ($FeSO_4$), ferrous chloride ($FeCl_2$), or Fe chelates at rates of 3 to 5 kg Fe per ha (2.7 to 4.5 lb Fe per acre) are preferable to soil applications.

10.10.4.3 Uptake and Assimilation by Higher Plants

The ferric (Fe^{3+}) form is dominant in soil, but ferrous (Fe^{2+}) is the physiologically active form. Hence, Fe has to be oxidized before assimilation. Iron uptake and nutrition are genetically controlled and not totally understood. Two mechanisms of Fe uptake have been identified in root tips and hairs. In the plasmalemmas of root cells near the root surfaces, Fe^{3+} is reduced to Fe^{2+} by the release of electrons and protons (Strategy 1). This release increases the activity of Fe^{3+} reductase. In Strategy 2, Fe^{3+} is taken up after chelation with plant-synthesized molecules called phytosiderophores. Ferric Fe may be oxidized in the roots or translocated as Fe^{3+} associated with citrate. Oxidation is thought to occur in the stems.

Iron is transported in the xylems, mainly to the chloroplasts, where its levels are controlled by reversible binding with ferric phosphoprotein and phytoferritin.

10.10.4.4 Nutrition in Higher Plants

Essential roles of Fe are related to changes in oxidation–reduction states and electron transfer reactions. Iron is a component in enzyme systems such as cytochrome oxidases, catalases, peroxidases, cytochromes, and heme-containing pigments. It it also a component of ferredoxin, a protein required for nitrate reduction, sulfate reduction, N_2 assimilation, and energy production via NADP). Indirect roles attributed to Fe include chlorophyll and protein synthesis, root tip meristem growth, and control of alanine synthesis.

10.10.4.5 Adequate Range and Nutritional Disorders

10.10.4.5.1 Sufficiency Range

The sufficiency range for Fe is not clearly established, although the range is 50 to 75 mg Fe per kg (ppm) in normal tissues.

10.10.4.5.2 Deficiency

Symptoms of Fe deficiency are similar to those of Mg because both play roles in chlorophyll production. However, because Fe is not mobile (Mg is), symptoms of Fe deficiency appear first on young leaves. Interveinal chlorosis appears. As the severity of the deficiency increases, chlorosis spreads to older leaves, which turn white and dry. Amino acids and nitrate (NO_3) tend to accumulate when plants are Fe-deficient.

Iron is unique among micronutrients because its availability and uptake can be influenced by plants. Plants within species are Fe-efficient or Fe-inefficient. Iron-efficient plants can acidify the rhizosphere and/or release siderophores that enhance Fe uptake.

10.10.4.5.3 Toxicity

Iron toxicity develops as a bronzing of the leaves, followed by tiny brown spots. It can often accumulate to 300 to 400 ppm without inducing toxicity.

10.10.4.6 Interactions with Other Essential Elements

An increase in pH (>7.0) after liming can result in Fe chlorosis, due primarily to the availability of Fe as ferric hydroxide at higher pH rather than the inhibitory effect of bicarbonate on Fe movement within plants. Nitrogen accentuates Fe deficiency due to increased growth of tissues. Nitrate-induced high pH levels in the root-free spaces and rhizospheres can restrict Fe uptake due to the effects of pH on Fe availability.

High levels of P decrease the solubility of Fe in plants. A P:Fe ratio of 29:1 is considered optimal for most plants. Potassium increases mobility and solubility of Fe in plants and may indirectly increase the rate of Fe uptake. Potassium is involved in maintaining the osmotic equilibrium of Strategy 1 for Fe uptake, and in the synthesis of phytosiderophores and organic acids of Strategy 2. Each of these micronutrients competes with Fe for uptake. Chloride may enhance Fe uptake.

10.10.5 Manganese (Mn)

The atomic number of manganese is 25; its atomic weight is 54.43. Scheele discovered it in 1774. McHargue proved it essential to plants in 1922.

10.10.5.1 Manganese in Soil

The weathering of primary Mn-containing ferromagnesium minerals forms secondary minerals such as pyrolusite (MnO_2) and manganite [MnO(OH)]. Manganese is also found in soils as Mn and Fe oxides, in part adsorbed at the surfaces of clay minerals. Anaerobic and acidic conditions favor the release of Mn into the soil solution, which is the most important fraction for plant nutrition. At slightly acidic pH, Mn^{3+} increases; at pH above 8, Mn^{4+} may be found. The availability of Mn depends also on organic matter content and microbial activity. Mn availability is significantly affected by soil pH; availability increases with decreasing pH, soil with temperature, organic matter content, and the form and method of fertilization. Mn^{2+} is easily leached from the soil.

Common fertilizer sources are $MnSO_4$ and $MnCl_2$. Manganese is also available in a chelated EDTA form.

10.10.5.2 Uptake and Assimilation by Higher Plants

As with Ca and Mg, the other essential divalent cations, Mn uptake is competitive and metabolically mediated. Levels of Mn in the roots are generally low. Manganese is mainly translocated in the xylems as Mn^{2+} or weakly combined with organic acids, preferentially to meristematic tissues. It is relatively immobile in plants.

10.10.5.3 Nutrition in Higher Plants

Changes between Mn^{2+} and Mn^{3+} allow Mn to be involved in oxidation–reduction and act as a cofactor for nitrite reductase, hydroxylamine reductase, indoleacetic oxidase, RNA polymerase, phosphokinases, and phosphotransferase.

Manganese is a component of superoxide dismutase, which neutralizes the free radicals formed by the splitting of water during the Hill reaction in photosynthesis. Similarly, Mn and superoxide dismutase may be involved in controlling the amounts of superoxides and free radicals generated by ozone and atmospheric pollutants. Manganese is involved in pollen germination and growth of the pollen tubes.

10.10.5.4 Adequate Range and Nutritional Disorders

10.10.5.4.1 Sufficiency Range

Foliar levels of Mn range from 10 to 200 mg per Mn kg (ppm); the sufficiency range is from 10 to 50 ppm.

10.10.5.4.2 Deficiency

Symptoms of Mn deficiency vary among plant species and often appear similar to deficiencies of Fe and Zn. One symptom is chlorosis between the veins of older leaves.

10.10.5.4.3 Toxicity

Manganese toxicity usually occurs in acid (pH <5.4) soils. Tolerance to Mn toxicity is species- and cultivar-dependent. Manganese toxicity appears as marginal yellowing of young leaves; central areas remain green. Necrotic spots may appear on various parts of leaves. High Mn levels in tree fruits appear as black specks (called measles) on stems and fruit.

10.10.5.5 Interactions with Other Elements

Nitrate-fed plants take up larger quantities of Mn than ammonium (NH_4)-fed plants. However, high ammonium fertilization can increase Mn uptake due to the acidification of the rhizospheres and increase availability for absorption. Phosphorus increases Mn uptake and Mg depresses Mn uptake by competition.

Increased pH reduces Mn solubility and uptake which can create a deficiency. Toxicity can occur in acid oil. Iron–Mn antagonism involves competition for absorption, interference in translocation, and possibly interference at functional sites in plants.

10.10.6 Molybdenum (Mo)

The atomic number of molybdenum is 42; its atomic weight is 95.95. Hzelm discovered it in 1782. Arnon and Stout proved it essential to plants in 1939.

10.10.6.1 Molybdenum in Soil

The main reservoir of Mo in the soil is molybdenite sulfide (Mo_2S). Molybdenum is found as a relatively insoluble salt in association with P, Ca, or Fe, and in association with organic matter. The weathering of these materials and the decomposition of organic matter release MoO_4^- into the soil solution. At low pH, Mo precipitates with Fe or Al.

Foliar applications of Mo at 50 to 100 g $NaMoO_4$ in 500 liters are used to correct deficiencies.

10.10.6.2 Uptake and Assimilation by Higher Plants

Molybdenum is taken up as the molybdate anion (MoO_4^-) and translocated, preferentially to the leaves.

10.10.6.3 Nutrition in Higher Plants

Molybdenum is an essential component of nitrate reductase (NR) and nitrogenase (NI). NR catalyzes the conversion of nitrate (NO_3) into nitrite (NO_2) during assimilatory nitrate reduction. Nitrogenase is required for the fixation of atmospheric nitrogen (N_2). In theory, plants fed exclusively with ammonium (NH_4) have no requirements for Mo.

10.10.6.4 Adequate Range and Nutritional Disorders

10.10.6.4.1 Sufficiency Range

The sufficiency range for Mo is 0.15 to 0.30 mg Mo per kg (ppm). Of all the essential nutrient elements, Mo is required in the smallest amount.

10.10.6.4.2 Deficiency

Molybdenum deficiencies may occur in leached, acid sandy soils or in soils naturally low in Mo. The Mo present in seed crops is usually sufficient to satisfy the requirements of developing plants. Deficiencies usually develop over several plant generations.

The most obvious symptom is leaf chlorosis resembling N deficiency. The chlorosis results from the need for Mo in nitrate reduction. It is followed by marginal curling and wilting, then withering and necrosis of the leaves. The symptoms initially appear in older leaves, then in younger leaves, until the growing points are killed.

In some *Brassica* species, the condition known as "whiptail," described as distorted leaf blades with the leaves showing perforations and/or marginal scorching, is due a Mo deficiency.

Intensive agriculture on sandy, acid-leached, and/or tropical soils require frequent Mo applications to support plant growth.

10.10.6.4.3 Toxicity

Molybdenum toxicity seldom occurs in the field, although some plants may contain over 15 ppm Mo. Molybdenum levels above 5 ppm in grasses can be toxic to grazing animals.

10.10.6.5 Interactions with Other Elements

Molybdenum uptake is inhibited by sulfates and enhanced by phosphates. During initial nutrient absorption, sulfates compete directly with molybdate for absorption sites on roots. Phosphates replace molybdate from the anion exchange sites at the surfaces of soil colloids. This increases Mo concentration in the soil solution and availability to plants.

10.10.7 Zinc (Zn)

The atomic number of zinc is 30; its atomic weight is 65.38. Zinc has been known since ancient times. Sommer and Lipman proved it essential to plants in 1926.

10.10.7.1 Zinc in Soil

The main primary mineral containing Zn is sphalerite, a sulfide mineral. In some silicate minerals, Zn substitutes for Fe and Mn. It is present in augite, biotite, and hornblende. After weathering of primary minerals, Zn may become adsorbed at the surfaces of clay particles, bind with organic matter, form hydrous oxide complexes, or remain in soil solution.

The main sources are zinc sulfates ($ZnSO_4{\cdot}H_2O$, $ZnSO_4{\cdot}6H_2O$, and $ZnSO_4{\cdot}7H_2O$) applied at rates from 50 to 100 kg $ZnSO_4$ per ha (44.7 to 89.3 lb per acre), depending on soil test results. Banding zinc fertilizers is preferable over broadcasting because Zn does not move in the soil. Other sources include zinc ammonium nitrate, zinc nitrate [$(Zn(NO_3)_2{\cdot}6H_2O)$], and zinc chelates. Amendments of chicken litter and animal manure also supply significant but variable amounts of Zn.

10.10.7.2 Uptake and Assimilation by Higher Plants

Zinc availability is related to its mobility; up to 95% of the Zn in soil moves by diffusion. Diffusion gradients and root depletion zones have been observed. Factors that limit the rate of diffusion of Zn to plant roots also reduce Zn availability. This is probably the most important reason why Zn deficiency often occurs on compacted soils or where root growth is restricted. Zinc is taken up mainly as the Zn^{2+} cation, although $ZnCl_2$ and Zn chelates may also be absorbed. The uptake of Zn^{2+} is active and metabolically controlled.

Zinc is transported radially across roots to the endodermis through the symplast to the xylem. Zinc is present in the xylem sap as an ion and does not appear to form complexes. It may move in the xylem by successive bindings to stable, slowly exchanging ligands as observed with Cu^{2+} and Fe^{3+}.

10.10.7.3 Nutrition in Higher Plants

The role of Zn is similar to that of manganese (Mn^{2+}) and magnesium (Mg^{2+}) ions and Zn is involved in binding substrate and enzyme in several enzyme systems. Carbonic anhydrase activity is highly

dependent on Zn supply. This enzyme promotes hydrolysis and hydration reactions involving carbonyl groups. It is localized in the cytoplasm of the chloroplast where it catalyzes the reaction between CO_2 and H_2O to form carbonic acid (H_2CO_3). Because the enzyme concentrates in the stroma, it protects proteins from denaturation resulting from local pH changes associated with hydrogen ion pumps and the incorporation of CO_2 into ribulose 1,5 bisphosphate.

In the cytoplasm, alcohol dehydrogenase catalyzes reduction of acetaldehyde to ethanol as part of glycolysis. In higher plants, this reaction occurs mainly in meristematic zones. Alternatively, in anaerobic respiration, Zn^{2+} catalyzes lactic acid dehydrogenase for the conversion of pyruvic acid to L-lactic acid.

In one of the three types of superoxide dismutase, the metal prosthetic group includes Zn and Cu. In the chloroplast, this enzyme catalyzes the conversion of the superoxide radical, O_2^-, to hydrogen peroxide (H_2O_2) and oxygen, protecting aerobic organisms from damage caused by oxygen. The H_2O produced is hydrolyzed by catalase.

In the absence of Zn, RNA polymerase is inactivated and RNA synthesis is impaired. Zinc deficiency is closely related to inhibition of RNA synthesis. The deficiency prevents the normal development of chloroplast grana. Zinc also stabilizes cytoplasmic ribosomes. It is required for enolases, glutamate dehydrogenase, D-glyceraldehyde-3-phosphate dehydrogenase, L- and D-lactic dehydrogenase, D-lactic cytochrome-c reductase, malic dehydrogenase, and aldolase. Some of the enzymes activated by Zn^{2+} can be activated by other divalent cations as Mg^{2+}, Mn^{2+}, Cu^{2+}, or Ca^{2+}.

Indirect evidence indicates that Zn is required to synthesize indoleacetic acid from tryptophan and may have a role related to starch formation in plant metabolism.

10.10.7.4 Adequate Range and Nutrition Disorders

10.10.7.4.1 Sufficiency Range

The sufficiency range for Zn in leaves is 15 to 50 mg Zn per kg (ppm). While Zn is present throughout plants, it is preferentially retained by the root systems.

10.10.7.4.2 Deficiency

One Zn deficiency symptom is chlorosis in the interveinal areas of leaves. The areas turn pale green, yellow, or even white. In monocotyledon species and particularly in maize, chlorotic bands form on both sides of the mid-ribs. In fruit trees, leaf development is restricted and unevenly distributed clusters or rosettes of small stiff leaves are formed; fewer buds appear and many remain closed. Symptoms of Zn deficiency in vegetable crops are more species-related than deficiency symptoms of other nutrient elements. Zinc deficiency is usually characterized by short internodes and chlorotic areas on older leaves.

10.10.7.4.3 Toxicity

At levels above 200 mg Zn per kg (ppm), Zn toxicity reduces root growth and leaf expansion, followed by chlorosis. High levels of Zn in the soil may also induce Fe, Mn, or P deficiencies.

10.10.7.5 Interactions with Other Elements

Excessive P interferes with Zn uptake, translocation, and metabolism. Excessive Zn depresses Fe uptake and can result in the development of Fe deficiency symptoms.

REFERENCES

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Part V

Diagnostic Procedures for Soil and Plant Analysis

11 Soil Analysis

11.1 INTRODUCTION

The management of a cropping system requires periodic evaluation that includes systematic testing. Knowing the physical and chemical status of the soil and the crop before and during the growing season are essential requirements for profitable production. This section focuses on the techniques of soil and plant analysis along with a discussion of diagnostic approaches. Many publications discuss these topics. The objective here is to present an overview of the basic principles and techniques associated with each of these procedures.

In 1951, the National Soil Test Work Group[1] stated, "There is good evidence that the competent use of soil tests can make a valuable contribution to the more intelligent management of the soil." The objectives of soil testing have changed little since they were first presented over 50 years ago:

1. To group soil into classes for the purpose of suggesting fertilizer and lime practices.
2. To predict the probability of getting a profitable response to the application of plant nutrient elements.
3. To help evaluate soil productivity.
4. To determine specific soil conditions that may be improved by addition of soil amendments or cultural practices.

Soil testing as practiced today fits Objectives 1 and 2. Farmers and growers routinely test soil to determine lime and fertilizer needs. Although acceptance of the first two objectives is nearly unanimous, opinions still differ about the practical application of Objective 2 (soil test interpretation in terms of the recommended application rates of fertilizer). Adjustments can be made on the basis of crop requirement, anticipated yield, management skill of the farmer, and economic goals. Objectives 3 and 4 advocate soil testing for diagnostic reasons — to show how test results can describe general conditions of the soil. From a long-term view, these objectives have far more importance than was generally recognized in the 1950s.

Although soil testing has a long development and application history, test performance still needs improvement. Modern analytical capabilities are advancing faster than test methodology. However, most soil testing procedures in use today are adequate to evaluate soil fertility status. Change is proceeding in several directions, including universal single-extraction reagent methods, repeated extractions, and equilibrium solutions.

Soil testing is the only means of specifying lime and fertilizer needs and describing nutrient element fertility status correctly. Without soil test results and/or without following recommendations based on soil tests, random lime and fertilizer use would seldom allow production of successful crop yields free of nutrient element stress. Unfortunately, such stresses are still common. About a quarter of the world's land surface is affected by some type of naturally occurring elemental stress. Even the best naturally fertile soils will suffer from intensive cropping if proper techniques are not followed to:

- Replace crop-removed nutrient elements
- Counter acidification
- Maintain proper nutrient element balances for optimum growth

TABLE 11.1
Soil Tests Based on Objectives

Test	Objective
Water, salt, and buffer pH levels	Soil reaction and lime requirement
Extractable elements:	
Major elements (P, K, Ca, Mg, NO_3, SO_4)	Nutrient element status
Micronutrients (B, Cl, Cu, Fe, Mo, Mn, Zn)	Nutrient element status
Other elements (Al, Na)	Toxicity
Trace elements and heavy metals (As, Cd, Co, Cr, Cu, Mn, Pb, Ni)	Toxicity
Organic matter content	Physical and chemical characteristics
Mechanical analysis	Soil texture classification
Soluble salts	Total salts in soil solution

11.2 SEQUENCE OF PROCEDURES

The value of a soil analysis result is no better than the quality of the sample assayed, determined by: (1) how the sample was taken from the field, (2) what conditions existed during transport to the laboratory, (3) the preparation techniques applied to the sample, (4) sample aliquot measurement, (5) laboratory factors, and (6) sample storage. Soil analysis follows a series of steps with field sampling, progressing to laboratory analysis, and eventually to interpretation as shown in Figure 11.1.

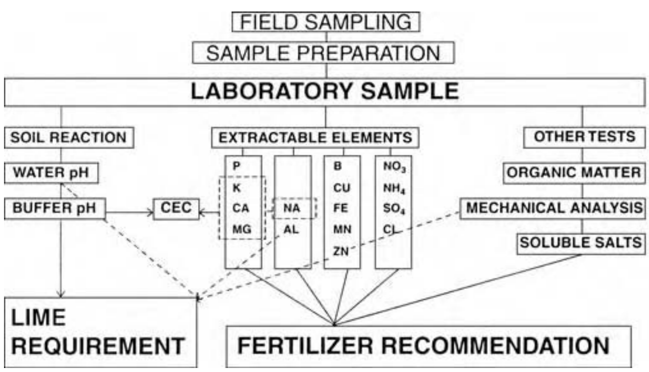


FIGURE 11.1 Sequence of soil analysis test procedure.

11.3 SAMPLING

Soils vary horizontally and vertically and the variation requires careful sampling technique. Topography and soil type are common factors for determining where, within sampling boundaries, to collect a single soil composite. The three most common sampling strategies are:

1. Simple random sampling
2. Stratified random sampling — selecting individual soil cores in a random pattern within a designated area
3. Systematic or grid sampling

Statistical considerations determine which method of sampling best defines the area under test evaluation. The depth of sampling is determined by any of several factors: horizonal characteristics (limiting depth to one soil horizon), depth of soil mixing for land preparation, and rooting depth of the growing or to-be-grown crop.

Because most field soils are not homogeneous naturally or because of past and/or current cultural practices, the challenge is to obtain a sample that is representative of the field under test. The common procedure is to take a number of individual cores to form a composite; the number of cores required to comprise a single composite sample ranges from as few as 4 to as many as 16.

Several studies show that variance for a determined soil test parameter is not substantially reduced by increasing the number of cores beyond 8. It is better to composite fewer cores and submit more multiple composites to a laboratory for analysis so that the mean analysis results for several composite samples are treated as a soil test value accompanied by a variance or range. Although this practice increases the time for and cost of soil testing, the variance detemined for the field under test adds a valuable factor to the test result.

The area represented by one composite soil sample is also an important consideration. Here again opinions vary considerably about the best procedure to follow. Some scientists recommend at least one composite per 5 acres (2 ha); others suggest one composite per 100 acres (40 ha). The decision becomes a management choice with or without knowledge of the homogeneity or lack of it in the field under test. Until the soil test level of a field is firmly established, it is best to divide it into equal-sized sections of no more than 10 acres (4 ha) each, and to gather a composite from each section. The soil test level is then determined by averaging the sum (with outliers discarded) of the test values of all the composites collected.

Coring should be random while avoiding areas that are markedly different in elevation and soil type. Coring should not be done near roads, fence rows, buildings, or tree lines. In fields to be treated as single units with soil type differences, cores from the differing soil types should not be mixed. Composites should be prepared from each major soil type for separate laboratory analysis. Some have suggested that, instead of dividing a field into equal-sized blocks, first divide it based on differences in soil type, and then further subdivide it into equal-sized blocks for sampling and compositing. Such a procedure is repeated until a pattern of homogeneity is established and previously separate sections can be combined to establish new boundaries for compositing.

The recommended procedure is to core to the plow (mixing) depth or to the depth of soil occupied by most plant roots in unplowed soils. Surface and subsurface (below plow depth) layers should not be mixed. Both horizons should be kept separate for individual analysis and interpretation. Normally, subsurface soils are not collected for analysis unless for specific purposes, such as for deep-rooted crops or when past nutrient element stress suggests a possible significant subsoil infertility problem. Deep soil profile samples are required for tests such as nitrate-nitrogen (NO_3-N).

Normally, sampling instructions do not specify a best time to collect samples, although some tests involve seasonal cycles. The best time when seasonal effects are minimal is midsummer to early fall. Some recommend sampling when plant tissue samples are collected for analysis, normally during mid or late summer months. However, the best time of the year for sampling is probably of less importance than taking samples at the same time each year so that test results can be tracked.

The following procedure for field sampling is recommended: for plowed fields, core to the plow depth; in unplowed planted or to-be-planted-in-row-crops fields, core to the depth at which at least 75% of the plant roots will be found.

By using varying rate applicators, lime and fertilizer application rates can be based on prepared grid maps that outline the areas of similar soil pH and levels of extractable elements. A range of



FIGURE 11.2 Hand tools for soil testing.

sampling techniques can be used to base the grid patterns, and lime and fertilizer application rates may be adjusted to maximize probable crop response and/or effect a reduction in soil pH and level of element variability.

Various devices can be used to collect soil cores; the more common types are Hoffer soil sampling tubes or soil augers as shown in Figure 11.2. Hydraulic-driven truck or offroad vehicle-mounted sampling devices can speed sample collection.

11.4 SOIL ANALYSIS PROCEDURES

11.4.1 Soil pH Testing

See Chapter 8 for extensive discussion of soil pH, testing methods, and interpretation of test results.

11.4.2 Testing for Phosphorus

TABLE 11.2
Phosphorus Testing Procedures

Test	Introduction Date	Adapted Range of Soil Properties
Morgan	1941	Acid soils with CECs below 10 meq/100 g
Bray P1	1945	Acid soils (pH_w <6.8) of moderate texture
Bray P2	1945	Acid soils in which rock phosphate is the primary P source and most P is in forms of calcium phosphate
Mehlich No. 1	1953	Acid (pH_w <6.5) coastal plain soils with low CECs (<10 meq/100 g) and low organic matter content (<5%)
Olsen	1954	Calcareous, alkaline, or neutral pH soils; P is mostly in various forms of calcium phosphate
AB-DTPA	1977	Calcareous, alkaline, or neutral pH soils; P is mostly in various forms of calcium phosphate; extractable P is highly correlated with Olsen P
Mehlich No. 3	1984	For a wide range of acid soils with extracted P correlating well with Bray P1 P for acid soils and with Olsen P for calcareous, alkaline, or neutral soils
0.01*M* $CaCl_2 \cdot 2H_2O$	2000	All soils

TABLE 11.3
Recommended Phosphorus Tests for Soils in U.S. Geographic Regions

Test	For Soil Type	Northeast	South	North Central	West
Mehlich No. 3[a]	Acid and calcareous	+	+	+	+
Mehlich No. 1[a]	Acid to neutral	+	+		
Bray/Kurtz	Acid to neutral	+		+	+
Olsen	Calcareous			+	+
AB-DTPA[a]	Calcareous			+	+
Morgan/modified Morgan[a]	Acid to neutral	+			+

[a] Multi-element extract that can be used to test for K, Ca, Mg, and trace elements.

Source: *Relevance of Soil Testing to Agriculture and the Environment*, Issue Paper 15, June 2000, CAST, Ames, IA. With permission.

TABLE 11.4
Phosphorus Extraction Reagents

Test	Extraction Reagent	Soil Aliquot (g)	Extractant Volume (mL)	Shaking Time (min)
Morgan	0.7*N* $NaC_2H_3O_2$ + 0.54*N* CH_3COOH, pH 4.8	5	25	30
Bray P1	0.03*N* NH_4F + 0.025*N* HCl	2	20	5
Bray P2	0.03*N* NH_4F + 0.1 *N*HCl	2	20	5
Mehlich No.1	0.05*N* HCl + 0.025*N* H_2SO_4	5	25	5
Olsen	0.5*N* $NaHCO_3$, pH 8.5	2.5	50	30
AB-DTPA	1*M* NH_4HCO_3 + 0.005*M* DTPA, pH 7.6	10	20	15
Mehlich No. 3	0.2*N* CH_3COOH + 0.015*N* NH_4F + 0.25*N* NH_4NO_3 + 0.013*N* HNO_3 + 0.001*M* DTPA	2.5 cm^3	25	5
Calcium chloride	0.01*M* $CaCl_2{\cdot}2H_2O$	10	100	120

TABLE 11.5
Phosphorus Extraction Reagents: Preparation and Procedure

Bray P1

Extraction Reagent (0.03N NH_4F in 0.025N HCl)

Mix 30 mL 1*N* ammonium fluoride (weigh 37 g NH_4F into a 1,000-mL volumetric flask and bring to volume with water; store in a polyethylene container and avoid prolonged contact with glass) with 50 mL 0.5*N* HCl (dilute 20.4 mL concentrated HCl to 500 mL with water] in a 1,000-mL volumetric flask and dilute to volume with water. Store in polyethylene. *Note*: Solution has a pH of 2.6 and is stable for more than 1 year.

Extraction Procedure

Weigh 2.0 g or scoop 1.70 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 20 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter through Whatman No. 2 paper, limiting filtration time to 10 min; save the filtrate.

Bray P2

Extraction Reagent (0.03N NH_4F in 0.1N HCl)

Mix 30 mL 1 *N* ammonium fluoride (weigh 37 g NH_4F into a 1,000-mL volumetric flask and bring to volume with water; store in a polyethylene container and avoid prolonged contact with glass) with 200 mL 0.5*N* HCl (pipette 20.4 mL concentrated HCl into a 500-mL volumetric flask and dilute to volume with water) in a 1,000-mL volumetric flask and bring to volume with water. Store in polyethylene. *Note*: Solution has a pH of 2.6 and is stable for more than 1 year.

Extraction Procedure

Weigh 2.0 g or scoop 1.70 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 20 mL extraction reagent and shake 5 min on a reciprocating shaker at a mininium of 180 oscillations/min. Immediately filter through Whatman No. 2 paper, limiting filtration time to 10 min; save the filtrate.

Olsen

TABLE 11.5 (CONTINUED)
Phosphorus Extraction Reagents: Preparation and Procedure

Extraction Reagent (0.5N $NaHCO_3$)

Weigh 42.0 g $NaHCO_3$ into a 1,000-mL volumetric flask and bring to volume with water. Adjust pH to 8.5 with 50% NaOH or 0.5*N* HCl. Add mineral oil to avoid exposure of the solution to air. Store in a polyethylene container. Check pH of the solution before use and adjust if necessary. *Note*: Maintenance of pH at 8.5 is essential.

Extraction Procedure

Weigh 2.5 g or scoop 2 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 250-mL extraction vessel. Add 50 mL extraction reagent and shake 30 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and collect the filtrate. *Caution*: Soil extraction is sensitive to temperature, changing 0.43 mg P/kg for every degree Celsius for soils containing 5 to 40 mg P/kg.

Mehlich No. 1

Extraction Reagent (0.05N HCl in 0.025N H_2SO_4)

Pipette 4.3 mL concentrated HCl and 0.7 mL concentrated H_2SO_4 into a 1,000-mL volumetric flask. Bring to volume with water.

Extraction Procedure

Weigh 5 g or scoop 5 cm^3 air-dried <10-mesh screened (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and collect the filtrate.

Mehlich No. 3

Extraction Reagent (0.2N CH_3COOH; 0.25N NH_4NO_3; 0.015N NH_4F; 0.13N HNO_3; 0.001M EDTA]

Ammonium fluoride-EDTA stock reagent: Add approximately 600 mL water to a 1,000-mL volumetric flask. Add 138.9 g NH_4F and dissolve. Add 73.05 g EDTA. Dissolve the mixture and bring to volume with water. Store in a plastic container.

Final extraction reagent mixture: Add approximately 3,000 mL water to a 4,000-mL volumetric flask. Add 80 g NH_4NO_3 and dissolve. Add 16 mL NH_4F-EDTA stock reagent (above) and mix well. Add 46 mL glacial acetic acid (CH_3COOH) and 3.28 mL concentrated HNO_3. Bring to volume with water and mix thoroughly. Achieve a final pH of 2.5 ± 0.1. Store in a plastic container.

Extraction Procedure

Scoop 5 cm^3 air-dried <10-mesh screened (2-mm) soil into an acid-washed 100-mL extraction vessel. Add 50 mL extraction reagent and shake 5 min on a reciprocating shaker. Immediately filter; collect the filtrate and save for elemental content determination. Store in a plastic container.

Morgan

Extraction Reagent (0.5N $NaC_2H_3O_2{\cdot}3H_2O$)

Weigh 100 g sodium acetate ($NaC_2H_3O_2{\cdot}3H_2O$) into a 1,000-mL volumetric flask. Add about 900 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH), adjust the pH to 4.8, and bring to volume with water.

Wolf Modification Extraction Reagent

Weigh 100 g sodium acetate ($NaC_2H_3O_2.3H_2O$) into a 1,000-mL volumetric flask and add about 300 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH) and 0.05 g DTPA (diethylenetriaminepentaacetic acid). Dilute to 950 mL with water, adjust the pH to 4.8, and bring to volume with water.

continued

TABLE 11.5 (CONTINUED)
Phosphorus Extraction Reagents: Preparation and Procedure

Extraction Procedure

Scoop 5 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and save the filtrate.

Ammonium Bicarbonate-DTPA (AB-DTPA)

Extraction Reagent (1M NH_4HCO_3-DPTA)

Obtain 0.005*M* DTPA (diethylenetriaminepentaacetic acid) solution by adding 9.85 g DTPA (acid form) to 4,500 mL water in a 5,000-mL volumetric flask. Shake constantly for 5 hr to dissolve the DTPA. Bring to 5,000 mL with water. The pH of the solution is stable.

To 900 mL of the 0.005*M* DTPA solution, add 79.06 g NH_4HCO_3 gradually and stir gently with a rod to facilitate dissolution and prevent effervescence when bicarbonate is added. Dilute solution to 1,000 mL with the 0.005*M* DTPA solution and mix gently with a rod. Adjust pH to 7.6 with slow agitation with a rod by adding 2*M* HCl. Store the ammonium bicarbonate-DTPA solution under mineral oil. Cheek the pH after storage and adjust dropwise with 2*M* HCl if necessary. *Note*: The cumulative volume of HCl added should not exceed 1 mL/L, after which a fresh solution should be prepared.

Extraction Procedure

Weigh 10 g air-dried <10-mesh sieved (2-mm) soil into a 125-mL conical flask. Add 20 mL extraction reagent and shake on an Eberbach or equivalent reciprocal shaker for exactly 15 min at 180 cycles/min with flasks kept open. Immediately filter the extracts through Whatman No. 42 paper and save the filtrater.

0.01*M* Calcium Chloride

Extraction Reagent (0.01M $CaCl_2{\cdot}2H_2O$)

Weigh 1.47 g calcium chloride dihydrate ($CaCl_2{\cdot}2H_2O$) into a 1000-mL volumetric flask and bring to volume with water.

Comment: $CaCl_2{\cdot}2H_2O$ may absorb water on standing and should be standardized by titration with EDTA at pH = 10 with Eriochrome black T as an indicator.

Extraction Procedure

Weigh 10.0 g air-dried <10-mesh sieved (2-mm) soil into a 250-mL polystyrene bottle. Add 100 mL 0.01*M* $CaCl_2{\cdot}2H_2O$ and shake mechanically at least 2 hr at room temperature (20°C; 68°F). Decant about 60 mL of the slurry into a 100-mL centrifuge tube and centrifuge 10 min at about 1,800 g. Carefully remove the supernatant for analysis.

TABLE 11.6
Interpretative Values for Extractable Phosphorus

Test	Critical Phosphorus Values (lb/acre)	
	Deficient	Excess
Morgan	<3.5	>6.5
Bray P1	<30	>60
Bray P2	<30	>60
Mehlich No. 1	<30	>100
Olsen	<11	>22
AB-DTPA	<15	>30
Mehlich No. 3	<36	>90

11.4.3 Testing for Cation Elements (Ca, Mg, K, and Na)

TABLE 11.7
Cation Testing Procedures

Test	Introduction Date	Adapted Range of Soil Properties
Morgan	1941	Acid soils with CECs below 10 meq/100 g
Ammonium acetate	1945	Acid to slightly alkaline soils
Mehlich No. 1	1953	Acid (pH_w <6.5) coastal plain sandy soils of low CEC (<10 meq/100 g) and low (<5%) organic matter content
Water	1965	Primarily alkaline soils
AB-DTPA	1977	Calcareous, alkaline, or neutral pH soils
Mehlich No. 3	1984	Wide range of acid soils
0.01*M* $CaCl_2 \cdot 2H_2O$	2000	All soils

TABLE 11.8
Cation Extraction Reagents

Test	Extraction Reagent	Soil Aliquort (g)	Extractant Volume (mL)	ShakingTime (min)
Morgan	0.7*N* $NaC_2H_3O_2$ + 0.54*N* CH_3COOH, pH 4.8	5	25	30
Ammonium acetate	1*N* $NH_4C_2H_3O_2$, pH 7.0	5	25	5
Water	Water	5	25	15
Mehlich No.1	0.05*N* HCl + 0.025*N* H_2SO_4	5	25	5
AB-DTPA	1*M* NH_4HCO_3 + 0.005*M* DTPA, pH 7.6	10	20	15
Mehlich No. 3	0.2*N* CH_3COOH + 0.015*N* NH_4F + 0.25*N* NH_4NO_3 + 0.013*N* HNO_3 + 0.001*M* DTPA	2.5 cm^3	25	5
Calcium chloride	0.01*M* $CaCl_2 \cdot 2H_2O$	10	100	120

TABLE 11.9
Cation Extraction Reagents: Preparation and Procedure

Neutral Normal Ammonium Acetate

Extraction Reagent (1N $NH_4C_2H_3O_2$, pH 7.0)

Dilute 57 mL *glacial* acetic acid (CH_3COOH) with water to approximately 500 mL. Add 69 mL concentrated NH_4OH. *Caution:* Use a fumehood. Add sufficient water to obtain a volume of 990 mL. After thoroughly mixing the solution, adjust the pH to 7.0 using NH_4OH or *glacial* CH_3COOH. Dilute to a final volume of 1,000 mL with water.

Alternate Method

Weigh 77.1 g ammonium acetate ($NH_4C_2H_3O_2$) in about 900 mL water in a 1,000-mL volumetric flash. After thoroughly mixing, adjust the pH to 7.0 using 3*N* CH_3COOH or 3*N* NH_4OH. Bring to volume with water.

Extraction Procedure

Weigh 5 g or scoop 4.25 cm^3 air-dried <10-mesh screened (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a mininium of 180 oscillations/min. Immediately filter and save the filtrate.

Mehlich No. 1

Extraction Reagent (0.05N HCl in 0.025N H_2SO_4)

Pipette 4.3 mL concentrated HCl and 0.7 mL concentrated H_2SO_4 into a 1,000-mL volumetric flask. Bring to volume with water.

Extraction Procedure

Weigh 5 g or scoop 5 cm^3 air-dried <10-mesh screened (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and save the filtrate.

Mehlich No. 3

Extraction Reagent (0.2N CH_3COOH; 0.25N NH_4NO_3; 0.015N NH_4F; 0.13N HNO_3; 0.001M EDTA)

Ammonium fluoride-EDTA stock reagent: Add approximately 600 mL water to a 1,000-mL volumetric flask. Add 138.9 g NH_4F and dissolve. Add 73.05 g EDTA. Dissolve the mixture and bring to volume with water. Store in a plastic container.

Final extraction reagent mixture: Add approximately 3,000 mL water to a 4,000-mL volumetric flask. Add 80 g NH_4NO_3 and dissolve. Add 16 mL NH_4F-EDTA stock reagent (above) and mix well. Add 46 mL *glacial* acetic acid (CH_3COOH) and 3.28 mL concentrated HNO_3. Bring to volume with water and mix thoroughly. Achieve a final pH of 2.5 ± 0.1. Store in a plastic container.

Extraction Procedure

Scoop 5 cm^3 air-dried <10-mesh screened (2-mm) soil into an acid-washed 100-mL extraction vessel. Add 50 mL extraction reagent and shake 5 min on a reciprocating shaker. Immediately filter and save the filtrate. Store in a plastic container.

Morgan

Extraction Reagent (0.5N $NaC_2H_3O_2{\cdot}3H_2O$)

Weigh 100 g sodium acetate ($NaC_2H_3O_2{\cdot}3H_2O$) into a 1,000-mL volumetric flask. Add about 900 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH), adjust the pH to 4.8, and bring to volume with water.

TABLE 11.9 (CONTINUED)
Cation Extraction Reagents: Preparation and Procedure

Wolf Modification Extraction Reagent

Weigh 100 g sodium acetate ($NaC_2H_3O_2 \cdot 3H_2O$) into a 1,000-mL volumetric flask and add about 300 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH) and 0.05 g DTPA. Dilute to 950 mL with water, adjust the pH to 4.8, and bring to volume with water.

Extraction Procedure

Scoop 5 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and save the filtrate.

Ammonium Bicarbonate-DTPA (AB-DTPA)

Extraction Reagent (1M NH_4HCO_3-DPTA)

Prepare 0.005*M* DTPA solution by adding 9.85 g DTPA (acid form) to 4,500 mL water in a 5,000-mL volumetric flask. Shake constantly for 5 h to dissolve the DTPA. Bring to 5,000 mL with water. The pH of the solution is stable.

To 900 mL of the 0.005*M* DTPA, gradually add 79.06 g NH_4HCO_3 and stir gently with a rod to facilitate dissolution and prevent effervescence. Dilute to 1,000 mL with the 0.005*M* DTPA solution and mix gently with a rod. Adjust pH to 7.6 with slow agitation and a rod by adding 2*M* HCl. Store AB-DTPA solution under mineral oil. Check pH after storage and adjust dropwise with 2*M* HCl if necessary. *Note*: The cumulative volume of HCl added should not exceed 1 mL/L, after which fresh solution should be prepared.

Extraction Procedure

Weigh 10 g air-dried <10-mesh sieved (2-mm) soil into a 125-mL conical flask. Add 20 mL extraction reagent and shake on an Eberbach or equivalent reciprocal shaker for exactly 15 min at 180 cycles/min with flasks kept open. Immediately filter the extracts through Whatman No. 42 paper and save the filtrate.

Water

Extraction Reagent

Pure water

Extraction Procedure

Weigh 5 g or scoop 4.25 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 25 mL water, seal the vessel with a stopper, and shake 30 min on a reciprocating shaker at a minimum of 180 oscillations/min. Allow to stand 15 min to let the bulk of the soil settle. Filter the supernatant liquid. *Note*: Discard the initial filtrate if it is turbid. Save the filtrate.

0.01*M* Calcium Chloride

Extraction Reagent (0.01M $CaCl_2 \cdot 2H_2O$)

Weigh 1.47 g calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) into a 1,000-mL volumetric flask and bring to volume with water. *Comment:* $CaCl_2 \cdot 2H_2O$ may absorb water on standing and should be standardized by titration with EDTA at pH = 10 with Eriochrome black T as an indicator.

Extraction Procedure

Weigh 10.0 g air-dried <10-mesh sieved (2-mm) soil into a 250-mL polystyrene bottle. Add 100 mL 0.01*M* $CaCl_2 \cdot 2H_2O$ and shake mechanically at least 2 hr at room temperature (20°C; 68°F). Decant about 60 mL of the slurry into a 100-mL centrifuge tube and centrifuge for 10 min at about 1,800 g. Carefully remove the supernatant for analysis.

TABLE 11.10
Indices for AB-DTPA-Extractable Potassium

Index	Soil Content (mg K/kg)
Low	0–60
Marginal	61–120
Adequate	>120

TABLE 11.11
Indices for Morgan-Extractable Potassium and Magnesium (mg/kg in Soil)

Index	Potassium	Magnesium
Low	0–50	0–12
Marginal	51–100	13–40
Adequate	>100	>40

11.4.4 Extractable Micronutrients (B, Cu, Fe, Mn, and Zn)

TABLE 11.12
Micronutrient Testing

Micronutrient	Interacting Factors	Method	Range at Critical Level (mg/kg)
Boron	Crop yield goal, pH, soil moisture, texture, organic matter, soil type	Hot water soluble	0.1–2.0
Copper	Crop, organic matter, pH, percent $CaCO_3$	Mehlich No. 1	0.1–10.0
		Mehlich No. 3	—
		DTPA	0.1–2.5
		AB-DTPA	—
		0.15*M* HCl	1.0–2.0
		Modified Olsen's	0.3–1.0
Iron	pH, percent $CaCO_3$, aeration, soil moisture, organic matter, CEC	DTPA	2.5–5.0
		AB-DTPA	4.0–5.0
		Modified Olsen's	10.0–16.0
Manganese	pH, texture, organic matter, percent $CaCO_3$	Mehlich No. 1	5.0 at pH 6.0, 10.0 at pH 7.0
		Mehlich No. 3	4.0 at pH 6.0, 8.0 at pH 7.0
		DTPA	1.0–5.0
		0.1*M* HC1	1.0–4.0
		0.03*M* H_3PO_4	10.0–20.0
		Modified Olsen's	2.0–5.0
Zinc	pH, percent $CaCO_3$, P, organic matter, percent clay, CEC	Mehlich No. 1	0.5–3.0
		Mehlich No. 3	1.0–2.0
		DTPA	0.2–2.0
		AB-DTPA	0.5–1.0
		Modified Olsen's	1.5–3.0
		0.1*M* HCl	1.0–5.0

TABLE 11.13
Extraction Reagents for Micronutrients

Mehlich No. 1 for Extraction of Zn

Extraction Reagent (0.05N HCl in 0.25N H_2SO_4)

Pipette 4.3 mL concentrated HCl and 0.7 mL concentrated H_2SO_4 into a 1,000-mL volumetric flask. Bring to volume with water.

Extraction Procedure

Weigh 5 g or scoop 5 cm^3 air-dried <10-mesh screened (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and save the filtrate.

Mehlich No. 3 for Extraction of B, Mn, and Zn

Extraction Reagent (0.2N CH_3COOH; 0.25N NH_4NO_3; 0.015N NH_4F; 0.13N HNO_3; 0.001M EDTA)

Ammonium fluoride-EDTA stock reagent: Add approximately 600 mL water to a 1,000-mL volumetric flask. Add 138.9 g NH_4F and dissolve. Add 73.05 g EDTA. Dissolve the mixture and bring to volume with water. Store in a plastic container.

Final extraction reagent mixture: Add approximately 3,000 mL water to a 4,000-mL volumetric flask. Add 80 g NH_4NO_3 and dissolve. Add 16 mL NH_4F-EDTA stock reagent (above) and mix well. Add 46 mL *glacial* CH_3COOH and 3.28 mL concentrated HNO_3. Bring to volume with water and mix thoroughly. Achieve a final pH of 2.5 ± 0.1. Store in a plastic container.

Extraction Procedure

Scoop 5 cm^3 air-dried <10-mesh screened (2-mm) soil into an acid-washed 100-mL extraction vessel. Add 50 mL extraction reagent and shake 5 min on a reciprocating shaker. Immediately filter and save the filtrate elemental content determination. Store in a plastic container.

Morgan for Extraction of B, Cu, Fe, Mn, and Zn

Extraction Reagent (0.5N $NaC_2H_3O_2 \cdot 3H_2O$)

Weigh 100 g sodium acetate ($NaC_2H_3O_2 \cdot 3H_2O$) into a 1,000-mL volumetric flask. Add about 900 mL water. Add 30 mL *glacial* CH_3COOH, adjust pH to 4.8, and bring to volume with water.

Wolf Modification Extraction Reagent

Weigh 100 g sodium acetate ($NaC_2H_3O_2 \cdot 3_2HO$) into a 1,000-mL volumetric flask and add about 300 mL water. Add 30 mL *glacial* CH_3COOH and 0.05 g DTPA. Dilute to 950 mL with water, adjust the pH to 4.8, and bring to volume with water.

Extraction Procedure

Scoop 5 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and save the filtrate.

Ammonium Bicarbonate-DTPA for Extraction of Cu, Fe, Mn, and Zn

Extraction Reagent (1M NH_4HCO_3-DPTA)

Prepare 0.005*M* DTPA solution by adding 9.85 g DTPA (acid form) to 4,500 mL water in a 5,000-mL volumetric flask. Shake constantly for 5 hr to dissolve the DTPA. Bring to 5,000 mL with water. The pH of the solution is stable.

To 900 mL of the 0.005*M* DTPA, gradually add 79.06 g NH_4HCO_3 and stir gently with a rod to facilitate dissolution and prevent effervescence. Dilute the solution to 1,000 mL with the 0.005*M* DTPA solution and mix gently with a rod. Adjust pH to 7.6 with slow agitation with a rod by adding 2*M* HCl. Store the AB-DTPA solution under mineral oil. Check the pH after storage and adjust dropwise with 2*M* HCl if necessary. *Note*: The cumulative volume of HCl added should not exceed 1 mL/L, after which a fresh solution should be prepared.

continued

TABLE 11.13 (CONTINUED)
Extraction Reagents for Micronutrients

Extraction Procedure

Weigh 10 g air-dried <10-mesh sieved (2-mm) soil into a 125-mL conical flask. Add 20 mL extraction reagent and shake on an Eberbach reciprocal or equivalent shaker for exactly 15 min at 180 cycles/min with flasks kept open. Immediately filter the extracts through Whatman No. 42 paper and save the filtrate.

DTPA for Extraction of Cu, Fe, Mn, and Zn

Extraction Reagent

Weigh 1.96 DTPA into a 1000-mL volumetric flask. Add 14.92 g triethanolaniine (TEA). Bring to approximately 950 mL with water. Add 1.47 g $CaCl_2 \cdot 2H_2O$. Bring to 1000 mL with water while adjusting the pH to exactly 7.3 with 6*N* HCl to achieve final concentration of 0.005*M* DTPA (acid form), 0.1*M* TEA, and 0.01*M* $CaCl_2$.

Extraction Procedure

Weigh 10 g or scoop 8.5 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 125-mL extraction vessel. Add 20 mL extraction reagent and shake on a reciprocating shaker for 2 hr at a minimum of 180 oscillations/min. Immediately filter and save the filtrate. *Note*: Samples shaken longer than 2 hr will give high results because final equilibrium of metal and soil is not reached in 2 hr.

0.01*M* Calcium Chloride for Extraction of B, Cu, Fe, Mn, and Zn

Extraction Reagent (0.01M $CaCl_2 \cdot 2H_2O$)

Weigh 1.47 g calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) into a 1,000-mL volumetric flask and bring to volume with water.

Comment: $CaCl_2 \cdot 2H_2O$ may absorb water on standing and should be standardized by titration with EDTA at pH = 10 with Eriochrome black T as an indicator.

Extraction Procedure

Weigh 10.0 g air-dried <10-mesh sieved (2-mm) soil into a 250-mL polystyrene bottle. Add 100 mL 0.01*M* $CaCl_2 \cdot 2H_2O$ and shake mechanically at least 2 hr at room temperature (20°C; 68°F). Decant about 60 mL of the slurry into a 100-mL centrifuge tube and centrifuge 10 min at about 1,800 g. Carefully remove the supernatant for analysis.

TABLE 11.14
Micronutrient Ratings and Recommendations Based on Tests with Different Extraction Reagents and Soils

				Crop/Soil Parameter (Rate, lb/Acre)[a]			
				Legume[c]		Nonlegume	
Micronutrient	**Rating[b]**	**Extraction Reagent Hot Water (ppm)**		**pH <6.8**	**pH >6.8**	**pH <6.8**	**pH >6.8**
Boron	VL	<0.4		1.5	2.0	1.0	1.5
	L	0.4–0.7		1.0	1.5	1.0	1.0
	M	0.8–1.2		1.0	1.0	0.5	0.5
	H	1.3–2.0		0.5	0.5	0	0.5
	VH	>2.0		0	0	0	0
				Soil			
		0.1*N* HCl (ppm)	**DTPA (ppm)**	**Mineral**	**Organic**		
Copper	VL	<0.3	<0.3	2	4		
	L	0.3–0.8	0.3–0.8	1	3		
	M	0.9–1.5	0.9–1.2	0–1	2		
	H	1.6–3.0	1.3–2.5	0	1		
	VH	>3.0	>2.5	0	0		
	pH <6.8	pH >6.8					
Iron	VL	0–3	0–5	3	3–5		
	L	4–11	5–10	2	2–4		
	M	12–24	11–16	0–2	1–2		
	H	25–50	17–25	0	0		
	VH	>50	>25	0	0		
	pH <6.8	pH >6.8					
Manganese	VL	0–5	0–4	4–5	5–7		
	L	0–14	4–8	2–4	3–5		
	M	15–29	9–12	0–2	3–5		
	H	30–50	13–30	0	0–1		
	VH	>50	>30	0	0		
				Low Phosphorus		**High Phosphorus**	
				<6.8 pH	**>6.8 pH**	**<6.8 pH**	**>6.8 pH**
Zinc	VL	<1.0	<0.5	5	6	7	8
	L	1.1–2.9	0.5–1.0	3–4	4–5	4–5	5–6
	M	3.0–5.0	1.1–3.0	1–2	2–3	2–3	2–4
	H	5.1–8.0	3.1–6.0	0	0–2	0–2	1–2
	VH	>8.0	>6.0	0	0	0	0

[a] Broadcast rates: Fe, Mn, and Zn are more efficient when applied in bands. Divide rates by three for band placement.
[b] VL = very low; L = low; M = medium; H = high; VH = very high.
[c] For legumes or other crops with high B requirements.

TABLE 11.15
Interpretation of Hot Water-Extractable Boron Tests

Category	B Content (mg/ha in Soil)
Insufficient	<1.0
Adequate for normal growth	1.0–2.0
High	2.1–5.0
Excessive	>5.0

TABLE 11.16
Indices for AB-DTPA-Extractable Micronutrients (mg/kg in Soil)

Category	Copper	Iron	Manganese	Zinc
Low	0.0–0.2	0.0–3.0	0.0–0.5	0.0–0.9
Marginal	0.3–0.5	3.1–5.0	0.6–1.0	1.0–1.5
Adequate	>0.5	>5.0	>1.0	>1.5

TABLE 11.17
Classification of Micronutrients (mg/L) into Fertility Classes

Micronutrient (Test)	Class 1 (Very Low)	Class 2 (Low)	Class 3 (Medium)	Class 4 (High)	Class 5 (Very High)
Boron (hot water)	<0.15	0.15	0.35	0.80	2.0
Copper (AAAc-EDTA)[a]	<0.7	0.7	2.0	6.0	18.0
Iron (AAAc-EDTA)	<30	30	75	200	500
Manganese (AAAc-EDTA)	<23	23	90	360	1400
Manganese (DTPA)	<4	4	14	50	170
Molybdenum (AAAc-EDTA)	<0.003	0.003	0.14	0.065	0.3
Zinc (AAAc-EDTA)	<0.5	0.5	1.5	5.0	15.0
Zinc (DTPA)	<0.2	0.2	0.7	2.4	8.0

Note: Classes 1 and 5 represent the 3 to 4% of the lowest and highest values, respectively; remaining percentages are divided among the middle classes.

[a] AAAc = acidified ammonium acetate.

Source: *Micronutrients and the Nutrient Status of Soils: A Global Study,* 1982, Soil Bulletin 63, United Nations Food and Agriculture Organization, Rome.

TABLE 11.18
Deficiency and Excess Concentration Ranges for Micronutrients

Micronutrient (Method)	Deficiency (mg/L)	Excess (mg/L)
Boron (hot water)	<0.3–0.5	>3–5
Copper (AAAca-EDTA)	<0.8–1.0	>17–25
Iron (AAAc-EDTA)	<3–35	—
Manganese (DTPA + pH correction)	<2–4	>15–200
Manganese (AAAc-EDTA + pH correction)	<10–25	1,300–2,000
Molybdenum (AAAc-EDTA + pH correction)	<0.002–0.005	0.3–1.0
Zinc (DTPA)	<0.4–0.6	>1–2
Zinc (AAAc-EDTA + pH correction)	<1.0–1.5	>2–30

Note: AAAc = acidified ammonium acetate.

Source: *Micronutrients and the Nutrient Status of Soils: A Global Study,* 1982, Soil Bulletin 63, United Nations Food and Agriculture Organization, Rome.

TABLE 11.19
Interpretation of Micronutrient Soil Data (mg/L Soil = 1.5 kg Mineral Soil)

	Available Micronutrients		
Micronutrient (Method)	Deficient	Medium	Excess
Boron (hot water)	<0.3–0.5	0.5–2	>3–5
Copper (AAAc-EDTA)	<0.8–1.0	2–10	>17–25
Manganese (AAAc + pH correction)	<10–25	10–500	>1,300
Zinc (DTPA)	<0.4–0.6	1–5	>10–20

Note: Hot water = Berger and Truog (1939) *Ind. Eng. Chem. Anal. Ed*., 11:540-545. AAAc = 0.5*M* ammonium acetate + acetic acid, pH 4.7), with 0.02*M* Na-EDTA (Lakanen and Ervio, (1971), *Suom. Maataloustiet. Seuran Julk.*, 123:232-233. pH corrections for Mn: at pH 6.5, factor 0.5; at pH 6, factor 1; at pH 5.5, factor 1.5. DTPA = 0.005*M*, pH 7.3 (Lindsay and Norwell, (1978), *Soil Sci. Soc. Amer. J.*, 42:421-428.

Source: *IFA World Fertilizer Use Manual*, 1992, International Fertilizer Association, Paris.

11.4.5 Testing Methods for Other Ions and Elements

TABLE 11.20
Extraction Reagents for Determining Ammonium and Nitrate

2*M* Potassium Chloride for Extraction of NH_4- and NO_3-N

Extraction Reagent (2M KCl)
Weigh 150 g KCl into a 1,000-mL volumetric flask and bring to volume with water.

Extraction Procedure
Weigh 10 g air-dried <10-mesh sieved (2-mm) soil into a 125-mL conical flask. Add 50 mL extraction reagent and shake on an Eberbach or equivalent reciprocal shaker exactly 15 min at 180 cycles/min. Filter the slurry through Whatman No. 42 paper and save the filtrate.

0.01M Calcium Chloride for Extraction of NH_4- and NO_3-N

Extraction Reagent (0.01M $CaCl_2{\cdot}2H_2O$)
Weigh 1.47 g calcium chloride dihydrate ($CaCl_2{\cdot}2H_2O$) into a 1,000-mL volumetric flask and bring to volume with water. *Comment*: $CaCl_2{\cdot}2H_2O$ may absorb water on standing and should be standardized by titration with EDTA at pH = 10 with Eriochrome black T as an indicator.

Extraction Procedure
Weigh 10.0 g air-dried <10-mesh sieved (2-mm) soil into a 250-mL polystyrene bottle. Add 100 mL 0.01*M* $CaCl_2{\cdot}2H_2O$ and shake mechanically for at least 2 hr at room temperature (20°C; 68°F). Decant about 60 mL of the slurry into a 100-mL centrifuge tube and centrifuge 10 min at about 1800 g. Carefully remove the supernatant for analysis.

0.01M Calcium Sulfate for Extraction of NO_3-N

Extraction Reagent (0.01M $CaSO_4{\cdot}2H_2O$)
Weigh 1.72 g calcium sulfate ($CaSO_4{\cdot}H_2O$) into a 1,000-mL volumetric flask and bring to volume with water.

Extraction Procedure
Weigh 5 g air-dried <10-mesh sieved (2-mm) soil into a 125-mL conical flask. Add 50 mL extraction reagent and shake on an Eberbach or equivalent reciprocal shaker exactly 15 min at 180 cycles/min. Filter the slurry through Whatman No. 2 paper and save the filtrate.

0.04M Ammonium Sulfate for Extraction of NO_3-N

Extraction Reagent [0.04M $(NH_4)_2SO_4$]
Weigh 5.28 g ammonium sulfate [$(NH_4)_2SO_4$] into a 1,000-mL volumetric flask and bring to volume with water.

Extraction Procedure
Weigh 5 g air-dried <10-mesh sieved (2-mm) soil into a 125-mL conical flask. Add 50 mL extraction reagent and shake on an Eberbach or equivalent reciprocal shaker exactly 15 min at 180 cycles/min. Filter the slurry through Whatman No. 2 paper and save the filtrate.

Morgan for extraction of NO_3-N

Extraction Reagent (0.5 N $NaC_2H_3O_2{\cdot}3H_2O$)
Weigh 100 g sodium acetate ($NaC_2H_3O_2{\cdot}3H_2O$) into a 1,000-mL volumetric flask. Add about 900 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH), adjust the pH to 4.8, and bring to volume with water.

Wolf Modification Extraction Reagent
Weigh 100 g sodium acetate ($NaC_2H_3O_2{\cdot}3H_2O$) into a 1,000-mL volumetric flask and add about 300 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH) and 0.05 g DTPA. Dilute to 950 mL with water, adjust the pH to 4.8, and bring to volume with water.

Extraction Procedure
Scoop 5 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and save the filtrate.

TABLE 11.21
Extraction Reagents for Determining Sulfate

Morgan

Extraction Reagent (0.5N $NaC_2H_3O_2 \cdot 3H_2O$)

Weigh 100 g sodium acetate ($NaC_2H_3O_2 \cdot 3H_2O$) into a 1,000-mL volumetric flask. Add about 900 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH), adjust the pH to 4.8, and bring to volume with water.

Wolf Modification Extraction Reagent

Weigh 100 g sodium acetate ($NaC_2H_3O_2 \cdot 3H_2O$) into a 1,000-mL volumetric flask and add about 300 mL water. Add 30 mL *glacial* acetic acid (CH_3COOH) and 0.05 g DTPA. Dilute to 950 mL with water, adjust the pH to 4.8, and bring to volume with water.

Extraction Procedure

Scoop 5 cm^3 air-dried <10-mesh sieved (2-mm) soil into a 50-mL extraction vessel. Add 25 mL extraction reagent and shake 5 min on a reciprocating shaker at a minimum of 180 oscillations/min. Immediately filter and save the filtrate.

0.01M Calcium Chloride

Extraction Reagent (0.01M $CaCl_2 \cdot 2H_2O$)

Weigh 1.47 g calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) into a 1,000-mL volumetric flask and bring to volume with water.

Comment: $CaCl_2 \cdot 2H_2O$ may absorb water on standing and should be standardized by titration with EDTA at pH = 10 with Eriochrome black T as an indicator.

Extraction Procedure

Weigh 10.0 g air-dried <10-mesh sieved (2-mm) soil into a 250-mL polystyrene bottle. Add 100 mL extraction reagent and shake mechanically at least 2 hr at room temperature (20°C; 68°F). Decant about 60 mL of the slurry into a 100-mL centrifuge tube and centrifuge 10 min at about 1,800 g. Carefully remove the supernatant for analysis.

11.4.6 Interpretation of Soil Test Values

TABLE 11.22
Definitions Related to Availability

Source	Definition
Bray (1954)[2]	Available forms of nutrient elements are forms whose variations in amount are responsible for significant variations in yield and response. The availability of these forms involves their chemical and physical natures and the ability of a plant to use its root system to forage for them.
Scarsbrook (1965)[3]	Available N is in the root zone in form readily absorbed by plant roots.
Brady (1974)[4]	The available portion of any element or compound in soil can be absorbed and assimilated by growing plants.
Barber (1984)[5]	An available or bioavailable nutrient element is present in a pool of ions in the soil and can move to plant roots during growth if the roots are near enough.
Dahnke and Johnson (1990)[6]	Nitrogen availability indices are measurents of the potential of a soil to supply N to plants when conditions are ideal for mineralization. They do not include existing inorganic N present when the soil is sampled.
Peck and Soltanpour (1991)[7]	A plant-available nutrient element usually means the chemical form or forms of an essential plant nutrient element in the soil whose variations in amounts are reflected in variations in plant growth and yield.
Troeh and Thompson (1993)[8]	An available nutrient element is the small portion of each essential plant nutrient element in the soil that is available in plants.
Black (1993)[9]	An available material is susceptible to absorption by plants; availability affects quantity. Biological index nutrient element availability estimate ratios of availabilities or values are proportional; actual availabilities cannot be measured.
Bundy and Meisinger (1994)[10]	Available N in soils and N present in forms, concentrations, and spatial positions that allow utilization by plants growing in the soil. Nitrogen availability indices are analyses or chemical or biological tests to measure or predict amounts of available N released from soil under a specified set of conditions.
SSSA (1987)[11]	Available nutrient elements are (1) amounts of a soil nutrient element in chemical forms accessible to plant roots or compounds likely to be convertible to such forms during the growing; or (2) the contents of legally designated available nutrient elements in fertilizers determined by specified laboratory procedures, which in most states constitute the legal bases for guarantees.

Source: Sumner, M.E., Ed., 2000, *Handbook of Soil Science*, CRC Press, Boca Raton, FL, p. D-4. With permission.

TABLE 11.23
Soil Nutrient Classifications

Classification	Interpretation
Very low to low	Very high probability of achieving a response to applied nutrient; unlikely probability of achieving a response to applied ameliorant for toxicity.
Moderately low	High probability of achieving a response to applied nutrient; possible or low probability of achieving a response to applied ameliorant for toxicity.
Marginal	Possible or low probability of achieving a response to applied nutrient; high probability of achieving a response to applied ameliorant for toxicity.
Adequate to high	Unlikely probability of achieving a response to applied nutrient; very high probability of achieving a response to applied ameliorant for toxicity.

Source: *Soil Analysis: An Interpretation Manual*, 1999, CSIRO Publishing, Collingwood, Australia.

TABLE 11.24
Soil Analysis Interpretation by Test Rating

Rating	Symbol	Interpretation
Low	L	Profitable response in almost all cases
Medium	M	Profitable response in most cases
High	H	Profitable response rare
Very high	VH	Not profitable to apply fertilizer
Excessive	E	Application may lower crop yield or quality

Source: *Soil Fertility Handbook*, 1998, Ontario Ministry of Agriculture, Toronto, Canada.

TABLE 11.25
Probable Crop Responses to P and K by Soil Rating

Soil Test Rating	Probability of Response (%)
Low	95–100
Medium	65–95
High	30–65
Very high	10–30

Source: *International Soil Fertility Manual,* 1995, Potash & Phosphate Institute, Norcross, GA. With permission.

11.4.7 Interpretive Values and Ranges for Various Soil Tests

TABLE 11.26
Fertility Ratings for Mehlich No. 3-Extractable P, K, Ca, and Mg (mg/dm^3)

Fertility Rating	P	K	Ca	Mg
Very low	0–35	0–25	0–234	0–27
Low	35–54	26–51	235–352	28–45
Medium	55–83	52–93	353–549	46–77
High	84+	94+	547+	78+

Source: Comparison of Mehlich 1 and Mehlich 3 extractants for P, K, Ca, Mg, Mn, Cu, and Zn in Atlantic coastal plain soils, *Commun. Soil Sci. Plant Anal.,* 20, 1707, 1989. With permission.

TABLE 11.27
Critical Values for Mehlich No. 3-Extractable Mn and Zn (mg/dm^3)

Soil pH	Mn	Zn
6.0	7.7	0.3
6.2	9.5	0.6
6.4	11.4	1.0
6.6	13.2	1.3
6.8	15.1	1.7
7.0	16.9	2.1

Source: Comparison of Mehlich 1 and Mehlich 3 extractants for P, K, Ca, Mg, Mn, Cu, and Zn in Atlantic coastal plain soils, *Commun. Soil Sci. Plant Anal.,* 20, 1707, 1989. With permission.

TABLE 11.28
Interpretive Values for Bray P1- and Olsen-Extractable P (ppm)

Test Rating	Bray P1	Olsen
Very low	1–9	1–5
Low	10–17	6–10
Medium	18–25	11–16
High	26–35	16–20
Very high	>35	>20

TABLE 11.29
Interpretive Values for Ammonium Acetate-Extractable K, Ca, and Mg (ppm)

Test Rating	K	Ca	Mg
Very low	1–50	1–250	1–50
Low	51–90	251–1,000	51–150
Medium	91–140	1,001–2,000	151–350
High	141–300	2,001–5,000	351–750
Very high	>300	>5,000	>750

Note: Soils with pH below 5.5 may be Ca- or Mg-deficient.

TABLE 11.30
Interpretive Values for DTPA-Extractable Cu, Fe, Mn, and Zn (ppm)

Test Rating	Cu	Fe	Mn	Zn
Very low	<0.2	0.1–0.6	<0.2	<0.2
Low	0.3–2.5	0.7–2.0	0.3–0.9	0.3–4.0
Medium	2.6–5.0	2.1–5.0	1.0–20	0.5–1.0
High	5.1–10	5.1–250	21–50	1.1–10
Very high	>10	>250	>50	>10

TABLE 11.31
Interpretive Values for Hot Water-Extractable B

Test Rating	B (ppm)
Very low	<2.0
Low	0.3–1.0
Medium	1.1–2.0
High	2.1–4.0
Very high	>4.1

TABLE 11.32
Interpretive Values for Water-Extractable N as the Nitrate Anion at 48-Inch Soil Depth (ppm)

Test Rating	Nitrogen Content Range
Very low	0–4
Low	5–9
Medium	10–14
High	>14

11.4.8 Fertilizer Recommendations Based on Soil Test Results

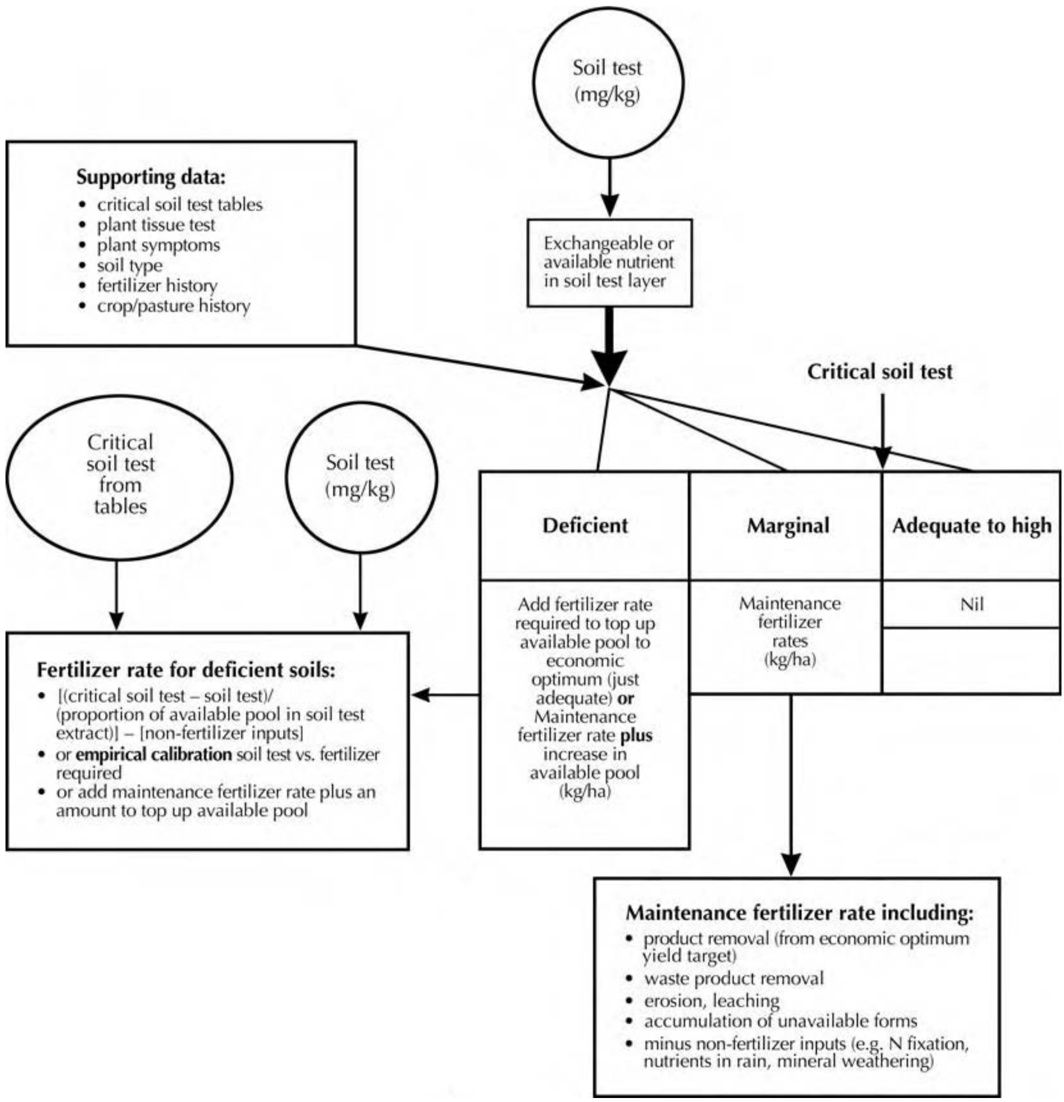


FIGURE 11.3 General guidelines for making fertilizer recommendations from a soil test for available nutrients. (*Source: Soil Analysis: An Interpretation Manual,* 1999, CSIRO Publishing, Collingwood, Australia. With permission.)

11.4.9 Cumulative Relative Frequencies of Levels of Soil Test K and P in North America

The following summaries show results of soil tests performed on approximately 2.5 million samples collected in Fall 2000 and Spring 2001 by 31 private and 34 public laboratories.

TABLE 11.33
Cumulative Relative Frequencies (%) for Ammonium Acetate Equivalent K in North America by Region

0–40 ppm	41–80 ppm	81–120 ppm	121–160 ppm	161–200 ppm	201–240 ppm	241–280 ppm	281–320 ppm	>320 ppm
North Central (993,489 Samples)								
1	13	37	62	78	88	93	96	100
Northeast (149,010 Samples)								
11	34	57	71	80	91	94	96	100
Northern Great Plains (124,143 Samples)								
0	2	7	18	30	43	58	71	100
Southeast (835,066 Samples)								
16	39	59	74	86	94	97	99	100
Southern Great Plains (247,380 Samples)								
2	9	19	28	38	46	54	60	100
West (99,227 Samples)								
3	14	33	52	67	77	83	87	100

Note: Regional category averages are means of state and province percentages and are not weighted by number of samples.
North Central: Missouri, Ohio, Kentucky, Illinois, Indiana, Iowa, Michigan, Wisconsin, Minnesota
Northeast: Prince Edward Island, New Brunswick, Maine, Massachusetts, Delaware, Quebec, New Hampshire, Maryland, Connecticut, New Jersey, Nova Scotia, Pennsylvania, New York, Vermont
Northern Great Plains: Alberta, Manitoba, South Dakota, Saskatchewan, North Dakota, Montana
Southeast: North Carolina, South Carolina, Alabama, Florida, Mississippi, Louisiana, Georgia, Tennessee, Virginia, Arkansas
Southern Great Plains: Oklahoma, Nebraska, Texas, Kansas
West: Oregon, Washington, California, Colorado, Nevada, New Mexico, Idaho, Utah, Arizona, Wyoming.

Source: *Soil Test Levels in North America: Summary Update*, Technical Bulletin 2001–1. Potash & Phosphate Institute, Norcross, GA. With permission.

TABLE 11.34
Cumulative Relative Frequencies (ppm) for Bray P-1 Equivalent Soil Test P in North America by Region and Sampling Density for States and Provinces

0–5 ppm	6–10 ppm	11–15 ppm	16–20 ppm	21–25 ppm	26–30 ppm	31–40 ppm	41–50 ppm	>50 ppm
North Central (1,056,873 Samples)								
2	10	20	30	40	49	63	74	100
Northeast (157,579 Samples)								
6	7	8	11	17	23	35	41	100
Northern Great Plains (137,338 Samples)								
9	39	62	77	85	90	94	97	100
Southeast (834,840 Samples)								
3	8	14	23	32	41	55	67	100
Southern Great Plains (250,914 Samples)								
6	119	34	48	59	67	78	84	100
West (104,385 Samples)								
3	12	24	35	45	54	67	76	100

Note: Regional category averages are means of state and province percentages and are not weighted by number of samples.
North Central: Missouri, Ohio, Kentucky, Illinois, Indiana, Iowa, Michigan, Wisconsin, Minnesota
Northeast: Prince Edward Island, New Brunswick, Maine, Massachusetts, Delaware, Quebec, New Hampshire, Maryland, Connecticut, New Jersey, Nova Scotia, Pennsylvania, New York, Vermont
Northern Great Plains: Alberta, Manitoba, South Dakota, Saskatchewan, North Dakota, Montana
Southeast: North Carolina, South Carolina, Alabama, Florida, Mississippi, Louisiana, Georgia, Tennessee, Virginia, Arkansas
Southern Great Plains: Oklahoma, Nebraska, Texas, Kansas
West: Oregon, Washington, California, Colorado, Nevada, New Mexico, Idaho, Utah, Arizona, Wyoming

Source: *Soil Test Levels in North America: Summary Update,* Technical Bulletin 2001–1. Potash & Phosphate Institute, Norcross, GA. With permission.

TABLE 11.35
Fractions of Samples Analyzed by Specific P and K Soil Tests

Phosphorus	%	Potassium	%
Mehlich No. 1	21	Mehlich No. 1	21
Mehlich No. 3	31	Mehlich No. 3	32
Bray P-1	30	Ammonium acetate	42
Olsen	11	Others	5
Others	7		

Source: *Soil Test Levels in North America: Summary Update*, Technical Bulletin 2001–1, Potash & Phosphate Institute, Norcross, GA. With permission.

TABLE 11.36
Soil Test Range Equivalents Assumed in Tables 11.33 and 11.34

Extraction Method	Categories Requested from Participating Laboratories (ppm)								
Ammonium bicarbonate-DTPA	0–1	2–3	4–5	6–7	8–9	10–11	12–15	16–19	>19
Bray and Kurtz P-1	0–5	6–10	11–15	16–20	21–25	26–30	31–40	41–50	>50
Bray and Kurtz P-2 (LSU only)	0–5	6–10	11–15	16–20	21–25	26–30	31–40	41–50	>50
Kelowa, modified	0–5	6–10	11–15	16–20	21–25	26–30	31–40	41–50	>50
Lancaster P	0–5	6–10	11–15	16–20	21–25	26–30	31–40	41–50	>50
Mehlich No. 1 P	0–3	4–6	7–9	10–12	13–15	16–18	19–24	25–30	>30
Mehlich No. 2 P	0–5	6–10	11–15	16–20	21–25	26–30	31–40	41–50	>50
Mehlich No. 3 P	0–5	6–10	11–15	16–20	21–25	26–30	31–40	41–50	>50
Morgan, Cornell	0–1				1–2	2–4	4–10	10–20	>20
Morgan, modified	0–3				4–7	8–11	11–20		>20
Olsen P (sodium bicarbonate)	0–3	4–7	8–11	17–22	23–27	28–32	33–43	44–54	>54
TAMU	0–5	6–11	12–16	17–22	23–27	28–32	33–43	44–54	>54
Ammonium acetate K	0–40	41–80	81–120	121–160	161–200	201–240	241–280	281–320	>320
Ammonium bicarbonate-DTPA	0–30	31–60	61–90	91–120	121–150	151–180	181–210	211–240	>240
Kelowna, modified	0–40	41–80	81–120	121–160	161–200	201–240	241–280	281–320	>320
Lancaster	0–40	41–80	81–120	121–160	161–200	201–240	241–280	281–320	>320
Mehlich No. 1 K	0–40	41–80	81–120	121–160	161–200	201–240	241–280	281–320	>320
Mehlich No. 3 K	0–40	41–80	81–120	121–160	161–200	201–240	241–280	281–320	>320
TAMU	0–45	46–90	91–135	136–180	181–225	226–270	271–315	316–360	>360
Water (NMSU only)	0–15	16–30	31–45	46–60	61–75	76–90	91–105	016–120	>120

Source: *Soil Test Levels in North America: Summary Update*, Technical Bulletin 2001–1, Potash & Phosphate Institute, Norcross, GA. With permission.

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12 Plant Analysis

12.1 INTRODUCTION

Plant analysis, also called leaf analysis, is a technique for determining the elemental contents of tissues of particular plant parts. It plays a major role in diagnosing mineral nutrition problems in the field and involves a series of steps (Figure 12.1):

- Sampling
- Sample preparation
- Laboratory analysis
- Interpretation

12.2 SAMPLING

Taking as samples the mature leaves exposed to full sunlight just below the growing tips on main branches or stems just before or when a plant begins its reproductive stage of growth is the preferred technique. In some cases, sampling may be done earlier or during the growth cycle of the plant if the intent is to collect leaf tissue of the same maturity. The important components for proper tissue collection are:

- Plant parts taken from a specific location on each plant
- Stage of plant growth or specific time of sampling

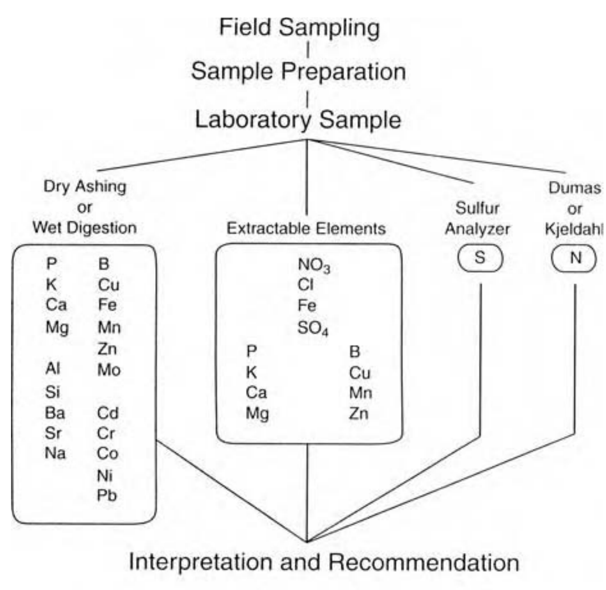


FIGURE 12.1 Sequence of plant analysis procedure.

- Number of parts taken per plant
- Number of plants selected for sampling

If the prescribed sampling directions are followed, the sampler should achieve reasonable statistical reliability. Sampling instructions are very specific in terms of plant part and stage of growth, since a comparison of assay results with established critical or standard values or sufficiency ranges is based on clearly identified plant parts taken at specified times. When specific sampling instructions are unknown, the general rule is to select upper leaves. Avoidance criteria are also crucial; plants to be avoided:

- Have suffered long-term climatic or nutritional stress
- Have been damaged mechanically or by insects
- Are infested with disease
- Are covered with dust, soil, or foliar-applied sprays unless the extraneous substances can be removed effectively
- Are border row plants or shaded leaves within the plant canopy
- Contain dead tissue

12.3 COMPARATIVE SAMPLING

Sampling two different populations of plants for comparative purposes, a highly desirable diagnostic procedure, poses a difficult problem, particularly when the type of stress produces substantial differences in plant growth. For example, when two or more sets of plants exhibit varying signs of a possible nutrient element insufficiency, collecting tissue for comparative purposes may be difficult because of the effect of the nutrient element stress on plant growth and development. Therefore, it is important whenever possible, to obtain plant tissue samples when the symptoms of stress first appear rather than waiting until substantial differences in plant charactistics are noted.

Finally, great care must be taken to ensure that representative samples are collected for such comparisons, and that the interpretation of the results takes into consideration the condition of the plants when they were sampled, whether normal in appearance or not, because of some type of stress.

12.4 INAPPROPRIATE SAMPLING

Although it is possible to assay just about any plant part or even an entire plant, the biological significance of such a result is dependent on the availability of interpretative data for the plant part collected, stage of plant growth, etc. For example, the assay of fruit or grain or the analysis of a whole plant or one of its parts at maturity or harvest does not usually provide reliable data on plant nutrition during earlier growth. The primary objective of plant analysis should be obtaining plant parts for which assay results can be compared with known interpretative values.

12.5 NUMBER OF PLANTS TO SAMPLE

The number of plants to sample depends on the general condition of the plants, soil homogeneity, and the purpose for which results will be used. Precision requirements will dictate the number of plant parts to be collected, the number of plants needed to constitute a composite sample, and the number of composite samples necessary to ensure sufficient replication. Normally, the mean value of several composite sample assays gives a more accurate estimate than a single assay result based on a single composite sample consisting of the same total number of individual samples.

12.6 LACK OF HOMOGENEITY

Lack of homogeneity within the plant and its parts is due to (1) movement of mobile elements from older tissue to newly developing tissue, (2) accumulation of immobile elements, and (3) reduction in dry matter content. Anatomical factors can affect the concentrations of elements found in whole leaves. Therefore, a sampling procedure that enhances the distribution effects of elements within the leaves will affect analysis results.

TABLE 12.1
Element Mobilities within Plants

Mobile	Variably Mobile	Immobile
Nitrogen	Sulfur	Calcium
Phosphorus	Copper	Manganese
Potassium	Zinc	Boron
Magnesium	Molybdenum	Iron

12.7 PLANT PARTS

Petioles are not parts of leaf blades and should not be included in leaf samples. However, for certain crops, e.g., grapes, sugar beets, and cotton, the petiole is the plant part to be assayed rather than the leaf blade. The petiole, as conductive tissue, is normally higher in elements like K, P, and nitrate-nitrogen (NO_3-N) than the attached leaf blade.

Compound leaves pose a problem for sampling because they comprise mixtures of petioles, conductive tissues, and leaf blades. In general, the recommended procedure is to collect a select leaf or leaves for such plants as tomato and potato, the terminal leaf at the end of a compound leaf, and middle pairs of leaves for nut trees such as pecan and walnut.

12.8 INITIAL SAMPLE HANDLING

Fresh plant tissue is perishable and must be kept cool and dry before delivery to the laboratory. If possible, the tissue should be air dried before shipment, and/or kept at reduced temperature (40 to 50°C; 104 to 122°F) to prevent decay because any deterioration will result in reduced dry weight and that will affect the analysis result.

12.9 DECONTAMINATION (WASHING)

Plant tissue covered with dust, soil, or foliar-applied materials that contain elements of interest requires decontamination before drying. Normally, decontamination (washing) is not recommended unless necessary. Mechanical wiping or brushing may be sufficient to remove large soil particles. Washing fresh plant tissue in a 0.1 to 0.4% P-free detergent solution followed by a rinse in pure water can effectively remove most extraneous materials.

Iron is the main element affected by decontamination; results of an assay for Fe without decontamination would be questionable. Contamination on rough or pubescent plant tissue surfaces is difficult to remove and poses a serious problem, as washing may not remove the contaminants effectively. Following an analysis, contamination can be detected by noting whether concentrations of Al, Si, and Fe in the assayed tissue are all equally high or if their concentrations among a series of plant analysis results track each other.

TABLE 12.2
Effects of Decomination (Washing) on Nutrient Element Concentrations in Orange Leaves

Nutrient Element	Unwashed	Detergent Wash[a]	Detergent/Acid Wash[b]
Nitrogen (%)	2.53	2.56	2.55
Phosphorus (%)	0.14	0.14	0.14
Potassium (%)	1.07	1.08	1.07
Calcium (%)	3.97	3.97	3.96
Magnesium (%)	0.42	0.40	0.42
Sodium (%)	0.061	0.066	0.065
Chloride (%)	0.022	0.028	0.064
Boron (mg/kg)	367	368	369
Copper (mg/kg)	5.6	5.1	5.0
Iron (mg/kg)	186	61	61
Manganese (mg/kg)	182	94	92
Zinc (mg/kg)	123	68	65

[a] Detergent wash: hand washed in 0.1% detergent and rinsed in deionized water.
[b] Detergent/acid wash: washed in 0.1% detergent, rinsed, dipped in 3% HCl for 2 min, and washed in deionized water.

Source: Effect of orange leaf washing techniques on removal of surface contaminants and nutrient losses, *Proc. Amer. Sci. Hort.* 89, 201, 1966. With permission.

12.10 ORGANIC MATTER DESTRUCTION

Organic matter destruction can be accomplished by high temperature thermal oxidation or by wet acid digestion; the former method is frequently referred as *dry ashing*, and the latter as *wet ashing*.

12.10.1 High Temperature (Dry) Ashing

1. Weigh 0.5 g dried (80°C; 176°F), 0.84-mm, (20-mesh screened) plant tissue into a 30-mL, high form porcelain and/or quartz crucible. *Note*: If an ashing aid is needed, add 5 mL HNO_3, or 5 mL 7% $Mg(NO_3)_2 \cdot 6H_2O$. Dry on a hot plate and continue with Step 2.
2. Place crucible in a rack, and the rack in a cool muffle furnace.
3. Set furnace to reach set temperature (500°C; 932°F) in about 2 hours.
4. After 4 to 8 hr of muffling, remove the crucible rack from the furnace and let cool.
5. Add 10 mL dilute acid mixture (300 mL HCl and 100 mL HNO_3 in 1,000 mL water) to dissolve the ash. *Note*: Dilute HNO_3 alone is frequently used to minimize the corrosive character of HCl when in contact with metal in the elemental analysis procedure.

12.10.2 Wet Acid Digestion in a Mixture of HNO_3 and $HClO_4$

1. Weigh 0.5 g dried (80°C; 176°F), 0.84-mm (20-mesh) plant tissue into a beaker or digestion tube.
2. Add 2.5 mL concentrated HNO_3. Cover the beaker with a watch glass or place a funnel into the mouth of the digestion tube. Let stand overnight.

3. Place covered beaker on a hot plate or digestion tube into a port of a digestion block and digest at 80°C (176°F) for 1 hour. Remove beaker or digestion tube from hot plate or block, and let cool.
4. Add 2.5 mL $HClO_4$. Replace watch glass or funnel, and heat at 180 to 200°C (356 to 392°F) for 2 to 3 hr or until digest is clear.
5. Remove watch glass or funnel, lower temperature to 100°C (212°F) until fumes of $HClO_4$ dissipate. If digest is not colorless, repeat Step 4.
6. Remove from the hot plate or digestion block and let cool.
7. Add pure water to digest to bring to 10 mL or other appropriate volume. Digest is ready for elemental assay.

12.10.3 Wet Acid Digestion in a Mixture of HNO_3 and 30% H_2O_2

1. Weigh 0.5 g dried (80°C; 176°F), 0.84-mm (20-mesh) plant tissue into a beaker or digestion tube.
2. Add 5.0 mL concentrated HNO_3. Cover with watch glass or place funnel into mouth of the digestion tube. Let stand overnight.
3. Place covered beaker on a hot plate or digestion tube into a port of digestion block and digest at 125°C (257°F) for 1 hour. Remove beaker or digestion tube from plate or block and let cool.
4. Add 3 mL 30% H_2O_2 to the beaker or digestion tube and digest at 125°C (257°F). Repeat additions of 30% H_2O_2 until digest is clear. Add HNO_3 as needed to prevent dryness.
5. When the digest is clear, remove the watch glass or funnel and reduce temperature of hot plate or block to 80°C (176°F). Take nearly to dryness. Residue should be colorless. If not, repeat Step 4.
6. Add 1:1 HNO_3 or HCl to bring to final volume of 10 mL. Clear solution is ready for elemental assay.

12.10.4 Wet Acid Digestion in H_2SO_4 and 30% H_2O_2

1. Weigh 0.5 g dried (80°C, 176°F) 0.84-mm (20-mesh) plant tissue into a beaker or digestion tube.
2. Add 3.5 mL concentrated H_2SO_4 and let stand 30 min.
3. Add 3.5 mL 30% H_2O_2.
4. Cover the beaker or place a funnel into the mouth of the digestion tube. Place beaker on a hot plate or digestion tube into a port of the digestion block. Heat 30 min at 350°C (662°F).
5. Remove beaker or tube from hot plate or digestion block and let cool.
6. Add 2-mL aliquots of 30% H_2O_2 and repeat digestion step until cool digest is clear.
7. Once the digest is clear, dilute to 20 mL with pure water. Digest is ready for elemental assay.

12.11 SAMPLE ANALYSIS

Analytical procedures suitable for the determination of elements in prepared plant tissue samples are described in two texts:

1. Jones, J.B., Jr., 2001, *Laboratory Guide for Conducting Soil Tests and Plant Analysis*, CRC Press, Boca Raton, FL.
2. Kalra, Y.P., Ed., 1998, *Handbook of Reference Methods for Plant Analysis*, CRC Press, Boca Raton, FL.

12.12 INTERPRETATION OF TEST RESULTS

Various techniques are used to interpret plant analysis results. The sufficiency range method is the most common. Critical values and standard reference values are used for particular crops. Many years of assay results are summarized, providing the interpreter with assay results that can be compared to currently determined results. In 1994, Markert published what he defined as "reference plant" composition values that can be compared to any plant analysis result as shown in Table 12.3.

TABLE 12.3
Markert's Reference Plant Composition for Major Elements and Micronutrients

Major Element	%	Micronutrient	ppm
Nitrogen	2.5	Boron	40
Phosphorus	0.2	Chlorine	2,000
Potassium	1.9	Copper	10
Calcium	1.0	Iron	150
Magnesium	0.2	Manganese	200
Sulfur	0.3	Molybdenum	0.5
Zinc	50		

Source: Progress Report on the Element Concentration Cadaster Project of INTECOL/IUBS, 25th General Assembly of IUBDS, 1994, Paris. With permission.

Diagnosing a plant analysis result based on critical or standard values or sufficiency ranges requires that the plant part and time of sampling be identical for the diagnosed tissue and for the source of the interpretative values. Those who now interpret plant analysis results for diagnostic purposes prefer working with the full range of concentrations from deficiency to excess. Such interpretive data is obtained from response curves as shown in Figures 12.2, 12.3, and 12.4. The slope and general configuration shown in Figure 12.3 are typical for describing the association of yield or plant response and macronutrient concentration in leaves or plants. Figure 12.4 better typifies the association between yield and micronutrient concentration.

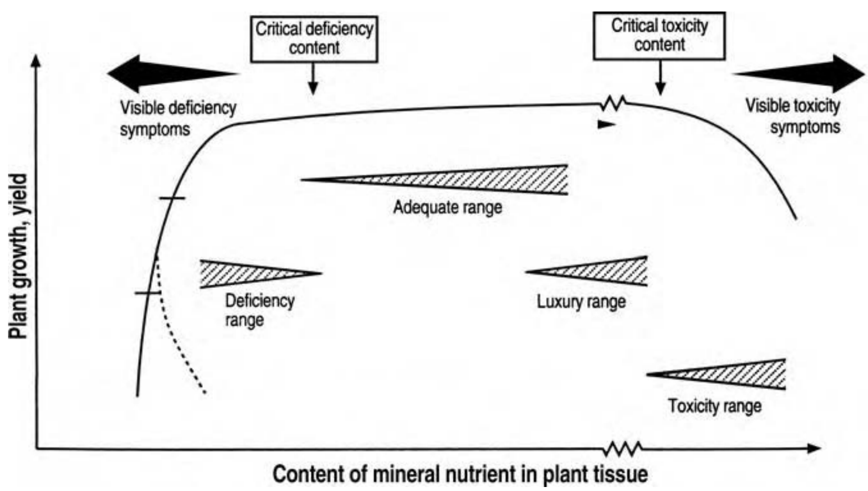


FIGURE 12.2 Relationship of nutrient element content and plant growth or yield.

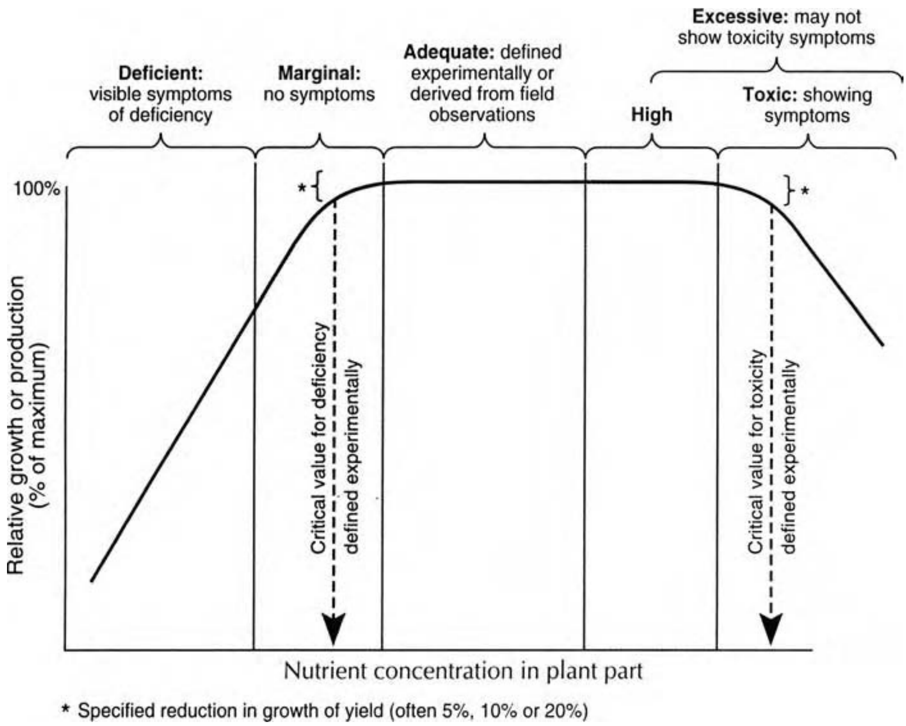


FIGURE 12.3 Representations of terms used to classify nutrient status. (*Source*: *Plant Analysis: An Interpretation Manual,* 1997, CSIRO Publishing, Collingwood, Australia. With permission.)

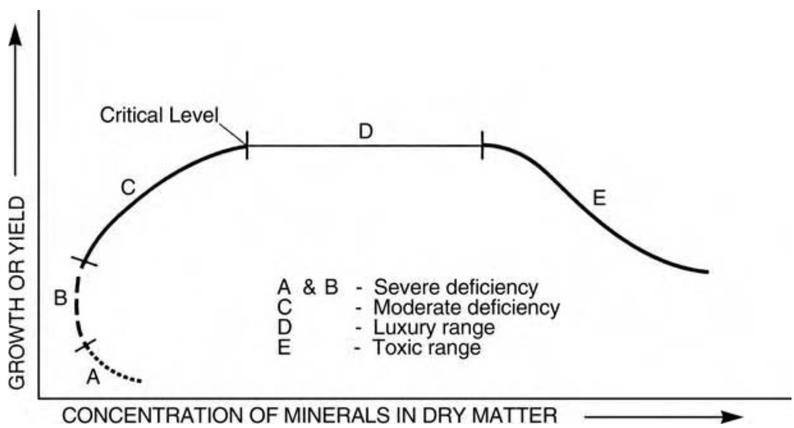


FIGURE 12.4 General relationship of plant growth or yield and elemental content. (*Source:* Smith, P.F., *Annu. Rev. Plant Physiol.*, 13, 81, 1962. With permission.)

The C shape seen on the left side of Figure 12.3 is called the "Steenbjerg Effect," and results from a combination of elemental concentrations or dilutions. The steep slope on the left of Figure 12.4 poses a significant sampling and analytical problem since a very small change in concentration results in a significant change in plant growth and/or yield.

A different concept of interpretation is the Diagnosis and Recommendation Integration System (DRIS). DRIS has been applied primarily for interpretations based on the major elements since the data base for the major elements is considerably larger than that for the micronutrients. DRIS will never totally replace the more traditional critical value or sufficiency range techniques.

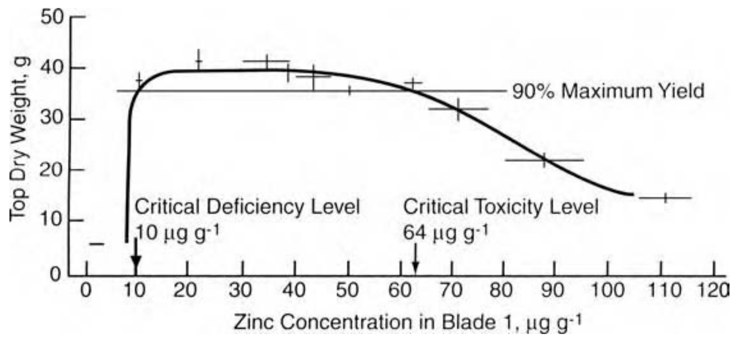


FIGURE 12.5 Relationship between zinc content of blade 1 of grain sorghum and top dry weight. (*Source*: Ohki, K., *Agron. J.*, 76, 253, 1984. With permission.)

12.13 LITERATURE REFERENCES FOR PLANT ANALYSIS INTERPRETATION

12.13.1 Interpretation Texts

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TABLE 12.4
Producers and Suppliers of Reference Materials for Elemental Composition Quality Control in Plant Analysis[a]

Code	Source
AAFC	Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Ottawa, Ontario K1A 0C6, Canada.
AMM	Faculty of Physics and Nuclear Techniques, University of Mining and Metallurgy, Al Mickiewicsa 30, 30-059 Krakow, Poland.
ARC	Food Research Institute, Laboratory of Food Chemistry, Agricultural Research Centre, SF-3 1600 Jokioinen, Finland.
BCR	Institute for Reference Materials and Measurements (IRMM), Retieseweg, B-2440 Geel, Belgium.
BOWEN	Dr. H.I.M. Bowen, West Down, West Street, Winterborne Kingston, Dorset DT11 9AT, Great Britain.
CALNRI	Central Analytical Laboratory, Nuclear Research Institute Rez plc, 25068 Rez, Czech Republic.
CANMET	Canadian Certified Reference Materials Project, Canada Centre for Mineral and Energy Technology, Natural Resources Canada, 555 Booth Street, Ottawa, Ontario K1A 0G1, Canada.
CSRM	Pb-Anal., Garbiarska 2, 04001 Kosice, Slovakia.
DL	AG Dillinger Huttenwerke, Postfach 1580, D-66748 Dillingen-Saar, Germany.
GBW	National Research Centre for Certified Reference Materials, 18 Bei San Huan Dong Hu, Hepingjie, 100013 Beijing, China.
IAEA	Analytical Quality Control Services, International Atomic Energy Agency, P.O. Box 100, A-1400 Wien, Austria.
ICHTJ	Commission of Trace Analysis, Committee for Analytical Chemistry of the Polish Academy of Sciences, Department of Analytical Chemistry, Institute of Nuclear Chemistry and Technology, ul. Dorodna 16, 03-195 Warszawa, Poland.
LIVSVER	Chemistry Division 2, Swedish National Food Administration, P.O. Box 622, 5–751 26 Uppsala, Sweden.
NIES	Division of Environmental Chemistry, National Institute for Environmental Studies, 16–2 Onagowa, Tsukuba, Ibaraki 305, Japan.
NIST	Standard Reference Materials Program, National Institute of Standards and Technology, Room 204, Building 202, Gaithersburg, MD 20899.
WSPTP	Western States Proficiency Testing Program, Department of Land, Air, and Water Resources, University of California, Davis, CA 95616.

[a] Primarily major government agencies; includes some academic, commercial, and private sources.

12.14 STEPS IN DIAGNOSTIC OBSERVATION

12.14.1 Visual Examination

When plants do not receive enough of a nutrient element to satisfy their needs, they grow poorly and develop abnormal appearances. They may also show abnormal growth patterns if supplied with toxic levels of an element. Symptoms of deficiency or excess are more visible on leaves but may appear on any part of a plant, including the stem, fruit, and roots. Symptoms of deficiency or toxicity are generally typical for each nutrient element. Therefore, it is possible to use the visual appearance of a sick plant to diagnose the cause of the disorder; as with animals — or human beings — the correct diagnosis of disorder is the first step in correction.

12.14.2 Information Required for Diagnosis

An essential requirement for visual diagnosis is the knowledge of what a healthy plant looks like. This is gained from a thorough knowledge of the plant — its life history and habits, how it looks and acts at all stages of growth. It is also necessary to know how seasonal conditions such as rainfall, temperature and light affect appearance.

The next essential is knowledge of the symptoms of each nutrient element disorder in the affected plant. It is also necessary to know how diseases, nematodes, and insect pests affect plants so their effects may not be confused with symptoms of nutrient element disorders.

12.14.3 Develop Case History of Problem

It is essential to develop a case history of the problem, including the cultural conditions experienced by the plants. The following information might be collected and analyzed:

Rainfall — How heavy were planting rains? How much and when did post-sowing rains fall? Was the pattern of rainfall normal or did drought or waterlogged conditions occur?

Temperature — Has weather been unseasonally hot or cold? Have frosts occurred; and if so, at what stage of growth were the plants?

Time of planting —Was planting normal, early or late?

Variety — What variety was planted. What was the source of seed? Was the seed treated with fungicides; if so, what compounds were used and at what rates?

Cultural history of paddock —What previous crops were grown? When were they sown and harvested? How did they yield? How was stubble handled? What fertilizers were applied and at what rates? Hahave the same problems appeared in previous crops?

Soil type and tests — Examine the soil for depth, presence of hardpans and root penetration, and for variations within the paddock. Have any soil tests been conducted; and if so, what are the results?

Plant analyses — Have plant samples been analyzed; what were the results? This information frequently allows some of the potential problems to be eliminated from further consideration.

12.14.4 Describe Symptoms

Record a general impression of the appearance of the crop: its color, density, height, stage of development and evenness of plant growth. Do all plants have the same general symptoms or are abnormal plants restricted to defined areas within the paddock? Are differences between areas of poor and good growth related to differences in topography, soil, drainage, cultural history, or management?

It is important to note the presence of all visible agents of damage such as insects, disease, and nematodes that can produce symptoms of abnormal growth. Frequently, the causal agent is invisible (for example, nutritional). Symptoms on individual plants should then be recorded in the following terms:

Location —The symptoms can be located on one organ only (e.g., on leaves or stems) or spread over entire plants. Categorize leaves as young (expanding or recently matured) or old, and each leaf as consisting of lamina and petiole, leaf tip and leaf base, veins and interveinal areas, and upper and lower surfaces.

Pests — Insects and diseases usually attack all leaves. Symptoms of nutritional disorders are usually restricted to certain leaves or only certain parts of leaves, for example, symptoms of Fe deficiency appear only in interveinal areas of younger leaves.

Color — Differences in color are important and should be noted not only as greens, yellows or reds, but as shades or tones, such as pale or dark yellow. Necrotic (dead) tissue may be present and its color should be noted also.

Size — Plants can be stunted, normal, or spindly in appearance. Some disorders cause excessive growth of some tissues, leading to outgrowths or galls. Other disorders cause smaller leaves to be produced.

Shape — Shape and size are somewhat related. However, shape can be altered while size remains constant. Some disorders cause marked changes in the shapes of leaves and flowers.

Orientation — The general growth of some plants is vertical, others sprawl horizontally. Disorders can alter the orientations of stems and leaves. For example, plants can have a limp, wilted appearance where normally upright stems droop.

Pattern —Development of a disorder follows a definite pattern. The early stages may be characterized by lesions that develop just inside the margins of the laminae near the leaf tips. As a disorder becomes more severe, the small lesions join together and expand until the leaves develop necrotic margins that progress from the tips toward the bases. By carefully examining a number of plants, both early and later stages of the disorder will be found.

12.14.5 Final Diagnosis

When all information has been collected, a decision can be made on the probable cause of the problem. First, consider the possibility that the symptoms were produced by insects, nematodes, disease organisms, or mechanical injury. When symptoms are found on a single plant, they are usually caused by one of these agents or genetic variations. Symptoms caused by nutritional disorders usually occur on several plants over a broad area related to a soil or management pattern. If disease, insect, or nematode attack or mechanical injury can be eliminated, the symptoms can be compared and matched with those characteristic of a nutritional disorder.

Different nutrient element disorders can sometimes produce somewhat similar symptoms. If more than one disorder is present, it is often difficult to sort out the symptoms that characterize each disorder. A nutrient element deficiency or toxicity may occur at any time during the life of a plant. However, the most typical symptoms are those that appear first; that is, during the early stages of the disorder, and these symptoms serve best to distinguish one disorder from another.

Any diagnosis based solely on visual symptoms should be regarded as preliminary. To confirm the diagnosis, help should be sought where possible from other methods such as soil, water and plant analyses, pot culture assays, field experiments, and test strips.

12.15 ADDITIONAL ASPECTS OF CROP DIAGNOSIS[1]

A crop diagnostician looks beyond fertility problems and soil tests for P, K, and other nutrient elements. The diagnostician must know and understand all the field conditions that impact crop growth. Such knowledge may help pinpoint a problem that is inducing or magnifying apparent nutrient element shortages. Look at all factors that influence crop growth, response to fertilization, and final yield.

Root zone — Soil must be granular and permeable for roots to expand and feed extensively. A crop will develop a root system 6 ft deep or more on some soils to reach water and nutrient elements. For that reason, it is desirable to know the fertility level of the subsoil. A shallow or compacted soil does not offer this root feeding zone. Wet or poorly drained soils produce shallow root systems. Proper drainage is important to early crop growth.

Temperature — Cool soil temperatures slow organic matter decomposition. This limits the releases of N, S, and other nutrient elements. Nutrient uptake is slower in cool soils, thus increasing deficiency potential. Nutrient elements diffuse more slowly in cool soils. Root activity is decreased.

Soil pH — Acid soil conditions reduce the availability of Ca, Mg, Mo, and P. They increase the availability of Fe, Mn, B, Cu, and Zn. N is most available between pH 6.0 and 7.0.

Insects — Do not mistake insect damage for a nutrient element deficiency. Examine roots, leaves, and stems for insect damage that may cause similar symptoms.

Diseases — Close study will show the difference between disease and nutrient element deficiency. Disease symptoms can often be detected with a small hand lens.

Moisture conditions — Dry soil conditions may create deficiencies. Boron, Cu, Mg, and K are good examples. This is why crops respond so well to such nutrients when they are well supplied in dry periods. Drought slows movement of nutrient elements to roots.

Soil salinity problems — Soluble salts and Na cause problems in some low rainfall areas. These conditions may occur only in part of a field — usually where a high water table exists, where poor quality water was used for irrigation, or where seepage water reaches the surface.

Weed identification — Herbicides and mechanical controls are more important than ever. Weeds rob agronomic plants of water, air, light, and nutrient elements. Some weeds may even release substances that inhibit crop growth. Learn to identify weeds and the materials used to control them.

Herbicide damage — Under certain conditions, plants may suffer from carryover herbicides or those applied in the current year. Be aware of possible drift from adjacent fields. Herbicide injury may also be affected by soil pH. Know the symptoms of herbicide damage and the interactions of herbicides with soil conditions.

Tillage practices — Some soils develop hardpans and require deep tillage. In conservation tillage, much of the fertilizer is broadcast and is on or near the surface. More P and K may be needed to build fertility. Band placing of some fertilizer near the seed may be helpful in such cases.

Hybrid or variety — Yield potential and adaptability to a given environment affect how a crop performs.

Plant spacing — Row width, uniform spacing of plants in rows, and number of plants per acre are important to yield.

Water management — Adequate surface or tile drainage is the key. Irrigation time and amount of water are of prime importance in good crop growth. Determine what the irrigation program has been.

Date of planting — This will affect rate of growth and plant appearance, as well as final yield potential in some cases.

Fertilizer placement — Under some conditions, a small amount of fertilizer near the roots is important for a fast start. The fertilizer may have been broadcast or applied too deeply. Strip or deep banding may be required in some situations.

Cultural practices — Knowing what has been done before you check conditions in the field may be the most important diagnostic technique

Get facts and record them —Cropping history, planting date, seeding rate, row width, tillage practices, depth and method of planting, past fertilizer, soil amendments, and weather conditions are all important issues. The more you know about a field before entering it, the better it can be diagnosed. Record all data. A checklist will ensure against forgetting vital information.

12.16 FACTORS AFFECTING NUTRIENT ELEMENT SYMPTOMS

Why do symptoms of plant nutrient element deficiency occur? Because insufficient amounts of an element in a form a plant can take up and use are present. That may occur because the soil is infertile and not enough of the nutrient element was added, but other factors also affect uptake and lead to the appearance of symptoms.

12.16.1 Root Zones

Crops differ a great deal in their development of root systems. The same crop may vary in the number and sizes of roots developed, depending on the environment and differences in plant genetics. Since some plant nutrient elements do not move far in the soil, the extent of the root system determines whether the plant gets enough of those nutrient elements. If root growth is shallow, plants may show deficiency symptoms even when the soil contains good supplies of those nutrient elements. Dry surface soil conditions may also limit nutrient element uptake if most of the available nutrient elements are in that zone (positional unavailability). When a deficiency symptom is noted, it is a good practice to examine the roots to see whether a restricted root zone may be contributing to the deficiency.

12.16.2 Temperature

Many growers note visual symptoms when plants are young, only to see the plants "grow out" of the symptoms as the season progresses. Often this is caused by the effects of temperature on root growth. If soil and air temperatures are cold, plants grow very slowly, root systems are small, and nutrient element uptake is low. Also, when air temperatures are too low or high, photosynthesis and respiration rates are affected. For example, if temperatures are too high at night, respiration continues at a high rate, burning up sugars and limiting the accumulation of carbohydrates.

12.16.3 Acidity or Alkalinity

When a visual symptom is noted, the degree of soil acidity or alkalinity in which the plant is growing should be evaluated. Very often this is closely related to the cause of the symptom.

The solubility and availability of many plant nutrient elements depend on soil pH. When the pH value rises above 6.0 to 6.5, elements such as Fe, Mn, Zn, and B decrease in solubility, perhaps to the point where the plants become deficient and show symptoms. In contrast, when soil pH is too acid (below 6.0), Mo becomes less soluble and a deficiency may occur.

Because of the influence of pH on plant nutrient element availability, it is essential to learn the liming history when a symptom is observed. Over-liming is easy to do on sandy soils and it produces symptoms of deficiencies of Fe, Mn, and Zn.

In some parts of the world, soils are naturally alkaline. This is often the case in arid regions where soils are only slightly weathered or where alkaline salts have accumulated. In areas of higher rainfall and outcroppings of limestone, the soil pH may be above 7.0. In such soils, deficiency symptoms of Fe, Mn, and Zn may be seen.

Soils in arid regions may also have problems of excess salinity (soluble salt) or Na (black alkali). These problems must be dealt with by establishing drainage, adding amendments if Na is involved, and leaching. Plants on such soils grow slowly, appear droughty, and may exhibit necrosis of the leaf margins.

12.16.4 Varieties and Genetic Factors

Sometimes a deficiency symptom may be noticed in one variety of a crop but not in another. This is not uncommon, but is often overlooked. Differences in genetic makeup may affect a plant's ability to take up and utilize certain nutrient elements. One variety may show symptoms of deficiency while another variety growing beside it may not show any symptoms.

12.16.5 Stage of Maturity[1]

As a plant nears maturity, it shows signs of old age that may include reddening, browning, or leaf tip or edge burn that may resemble a deficiency symptom. In fact, the two conditions are related. As a plant grows older, it may run out of N or K and may mature before it reaches its full yield potential. Some crops are sensitive to a delicate balance between the amount of N required for full yield and the amount that may be too little or too much. Visual symptoms help us recognize the correct amount.

12.17 MANAGEMENT PROGRAM FOR PRODUCING AND SUSTAINING HIGH YIELD

Developing a fundamental planning process that estimates attainable yield levels for each field while recognizing controllable limiting factors and their interactions for the cropping system is a challenge. Producing high yields often requires on-farm experimentation and setting a yield goal that is slightly out of reach. All input levels, from seeding rate to variety selection to fertilizer rate,

are set assuming the yield can be obtained, and practices applicable to whole fields and farms can be utilized:

- A focus on timeliness of all operations and a record-keeping system that allows quantification of what works and does not work.
- Use of technologies such as genetically enhanced varieties and site-specific management to control risk
- Long-term dedication to soil improvement, including physical, chemical, and biological properties. Individuals who produce top yields seldom do so overnight because soil properties, water holding capacity, and subsoil characteristics can be improved, but only over a period of several years.
- A constant watch for yield-limiting factors and dedication to removal of yield-limiting factors where possible. Insufficient soil fertility is an example of a controllable limiting factor that can be profitably removed, given sufficient time.

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Part VI

Reference Materials and Appendices

13 Weights, Measures, and Conversion Factors

TABLE 13.1
Avoirdupois Weight

Unit	Equivalent
1 dram (dr)	27 11/32 grains (gr)
1 ounce (oz)	16 drams (dr)
1 pound (lb)	16 ounces (oz)
1 quarter	25 pounds (lb)
1 hundredweight (cwt)	100 pounds, 4 quarters, 112 pounds (British)
1 ton (T)	2,000 pounds, 20 hundredweight

TABLE 13.2
U.S. Dry Measure

Unit	Equivalent
2 pints (pt)	1 quart (qt)
8 quarts (qt)	1 peck (pk)
4 pecks (pk)	1 bushel (bu)
1 bushel (bu)	2,150.42 cubic inches, 1.2444 cubic feet, 35.238 liters, 64 pints (dry)[a], 32 quarts (dry)[a], 0.30478 barrels
1 barrel (bbl)	3.281 bushels (bu), 105.0 quarts (dry)[a], 7,056 cubic inches, 4.0833 cubic feet

[a] In the U.S. system, the dry measure pint and quart are about 16% larger than their liquid measure equivalents.

TABLE 13.3
U.S. Liquid Measure

Unit	Equivalent
1 teaspoon (tsp)	1/6 ounce
1 tablespoon (tbsp)	1/2 ounce
4 fluid ounces	1 gill
4 gills	1 pint
2 pints	1 quart
4 quarts	1 gallon
31 1/2 gallons	1 barrel
2 barrels	1 hogshead

TABLE 13.4
Linear Measure

Unit	Equivalent
1 inch (in.)	0.0833 feet
1 foot (ft)	12 inches
1 yard (yd)	36 inches, 3 feet
1 rod (rd)	16 1/2 feet, 200 inches, 5 5/9 yards, 25 links
1 chain	4 rods, 100 links, 66 feet
1 mile	5,280 feet, 1,760 yards, 8,000 links, 320 rods, 80 chains
1 span	9 inches
1 hand	4 inches

TABLE 13.5
Square Measure

Unit	Equivalent
1 square inch (sq in.)	0.0069444 square feet
1 square foot (sq ft)	144 square inches
1 square yard (sq yd)	1,296 square inches, 9 square feet
1 square rod (sq rd)	272 1/4 square feet, 30 1/4 square yards
1 square chain (sq ch)	4,356 square feet, 16 square rods
1 acre (A)	43,560 square feet, 4,840 square yards, 160 square rods, 10 square chains, a square area 208.71 feet on each side or rectangle 200 feet by 217.8 feet
1 section	640 acres, 1 square mile
1 quarter (1/4 section)	160 acres
1 township (Twp)	36 square miles

TABLE 13.6
Common Conversions[a]

Unit	Equivalent
1 U.S. short ton	2,000 U.S. pounds (lb)
1 British long ton	2,240 U.S. pounds (lb)
1 metric ton (1,000 kg)	2,204.6 U.S. pounds (lb)
1 fluid ounce (oz)	29.57 cubic centimeters (cc)
1 quart (qt)	32 fluid ounces (oz), 946 cubic centimeters (cc)
1 liter (L)	1.0567 quarts (liquid)
1 gallon (U.S. standard)	128 fluid ounces (oz), 231 cubic inches (cu. in.), 3,785 cubic centimeters (cm^3)
1 gallon (Imperial)	277 cubic inches, 4.543 liters (L), 1.20095 U.S. gallons (gal)
1 gallon of water	3,788 grams (g), 8.345 pounds (lb)
1 ounce (oz)	28.35 grams (g)
1 pound (lb)	454 grams (g)
1 inch (in)	2.54 centimeters (cm)
1 centimeter (cm)	0.3937 inches (in.)
1 meter (m)	39.37 inches (in.)
1 yard	0.9144 meters (m)
1 kilometer (km)	3,280 feet 10 inches, 0.62137 mile
1 cubic inch	16.39 cubic centimeters (cc), 0.0164 liter (L)
1 cubic foot	28.32 liters (L), 7.4805 gallons (gal)
1 acre foot of soil	4,000,000 pounds (lb)
1 acre foot of water	43,560 cubic feet or 325,851 gallons (gal)
1 part per million (ppm)	2.72 lb per acre foot of water
1 ppm × 0.00136	tons of salt per acre foot of water
1 cubic foot per second	450 galllons per minute, 2 acre feet per day
1 gallon per minute	1/450 cubic feet per second
1 ton per acre	20.8 grams per square foot, 1 lb per 21.78 square foot (4 feet, 8 inches each way), 1 kilogram per 48 square feet

[a] Conversions involving volume of liquid to weight are based on standard conditions of room temperature (7°F or 20°C) and sea level barometric pressure. Such conversions will vary depending upon actual temperature and pressure.

TABLE 13.7
Factors for Converting U.S. Units into SI Units

U.S. Unit	SI Unit	Multiply U.S. Unit by Number below to Obtain SI Unit
Ångstrom	Nanometer, nm	10^{-1}
Atmosphere	Megapascal, MPa	0.101
Bar	Megapascal, MPa	101
Calorie	Joule, J	4.19
Cubic foot	Liter, L	28.3
Cubic inch	Cubic meter, m^3	1.64×10^{-5}
Curie	Becquerel, Bq	3.7×10^{10}
Degrees, °C (+273, temperature)	Degrees K (no degree symbol)	1
Degrees, °F (–32, temperature)	Degrees, °C	0.556
Dyne	Newton, N	10^{-5}
Erg	Joule, J	10^{-7}
Foot	Meter, m	0.305
Gallon	Liter, L	3.78
Gallon per acre	Liter per ha	9.35
Inch	Centimeter, cm	2.54
Micron	Micrometer, pm	1
Mile	Kilometer, km	1.61
Mile per hour	Meter per second	0.477
Millimho per cm	Decisiemens per m, dSm	1
Ounce (weight)	Gram, g	28.4
Ounce (fluid)	Liter, L	2.96×10^{-2}
Pint	Liter, L	0.473
Pound	Gram, g	454
Pound per acre	Kilogram per ha	1.12
Pound per cubic foot	Kilogram per m^3	16.02
Pound per square foot	Pascal, Pa	47.9
Pound per square inch	Pascal, Pa	6.9×10^3
Quart	Liter, L	0.946
Square foot	Square meter, m^2	9.29×10^{-2}
Square inch	Square cm, cm^2	6.45
Square mile	Square kilometer, km^2	2.59
Ton (2,000 lb)	Kilogram, kg	907
Ton per acre	Megagram per ha, Mg/ha	2.24

TABLE 13.8
Convenient Conversion Factors

Factor	Multiply by	To Get
Acres	0.4048	Hectares
Acres	43,560	Square feet
Acres	160	Square rods
Acres	4,840	Square yards
Acres	1,076.4	Square feet
Bushels	4	Pecks
Bushels	64	Pints
Bushels	32	Quarts
Centimeters	0.3937	Inches
Centimeters	0.01	Meters
Cubic centimeters	0.03382	Ounces (liquid)
Cubic feet	1,728	Cubic inches
Cubic feet	0.03704	Cubic yards
Cubic feet	7.4805	Gallons
Cubic feet	29.92	Quarts (liquid)
Cubic yards	27	Cubic feet
Cubic yards	46,656	Cubic inches
Cubic yards	202	Gallons
Feet	30.48	Centimeters
Feet	12	Inches
Feet	0.3048	Meters
Feet	0.060606	Rods
Feet	1/3 or 0.33333	Yards
Feet per minute	0.01136	Miles per hour
Gallons	0.1337	Cubic feet
Gallons	4	Quarts (liquid)
Gallons of water	8.3453	Pounds of water
Grams	15.43	Grains
Grams	0.001	Kilograms
Grams	1,000	Milligrams
Grams	0.0353	Ounces
Grams per liter	1.000	Parts per million
Hectares	2.471	Acres
inches	2.54	Centimeters
Inches	0.08333	Feet
Kilograms	1,000	Grams
Kilograms	2.205	Pounds
Kilograms per hectare	0.892	Pounds per acre
Kilometers	3,281	Feet
Kilometers	0.6214	Miles
Liters	1,000	Cubic centimeters
Liters	0.0353	Cubic feet
Liters	61.02	Cubic inches
Liters	0.2642	Gallons
Liters	1.057	Quarts (liquid)
Meters	100	Centimeters
Meters	3.2181	Feet
Meters	39.37	Inches

continued

TABLE 13.8 (CONTINUED)
Convenient Conversion Factors

Factor	Multiply by	To Get
Miles	5,280	Feet
Miles	63,360	Inches
Miles	320	Rods
Miles	1,760	Yards
Miles per hour	88	Feet per minute
Miles per hour	1.467	Feet per second
Miles per minute	60	Miles per hour
Ounces (dry)	0.0625	Pounds
Ounces (liquid)	0.0625	Pints (liquid)
Ounces (liquid)	0.03125	Quarts (liquid)
Parts per million	8.345	Pounds per million gallons water
Pecks	16	Pints (dry)
Pecks	8	Quarts (dry)
Pints (dry)	0.5	Quarts (dry)
Pints (liquid)	16	Ounces (liquid)
Pounds	453.5924	Grams
Pounds	16	Ounces
Pounds of water	0.1198	Gallons
Quarts (liquid)	0.9463	Liters
Quarts (liquid)	32	Ounces (liquid)
Quarts (liquid)	2	Pints (liquid)
Rods	16.5	Feet
Rods	5.5	Yards
Square feet	144	Square inches
Square feet	0.11111	Square yards
Square inches	0.00694	Square feet
Square miles	640	Acres
Square miles	27,878,400	Square feet
Square rods	0.00625	Acres
Square rods	272.25	Square feet
Square yards	0.0002066	Acres
Square yards	9	Square feet
Square yards	1,296	Square inches
Temperature (°C) + 17.98	1.8	Temperature, °F
Temperature (°F) − 32	5/9 or 0.5555	Temperature, °C
Tons	907.1849	Kilograms
Tons	2,000	Pounds
Tons, long	2,240	Pounds
Yards	3	Feet
Yards	36	Inches
Yards	0.9144	Meters

TABLE 13.9
Soil Analysis Values

Major Cation	lb/acre	ppm (mg/kg)	kg/ha	cmol/100 g (meq/100 g)
Calcium (Ca^{2+})	4,999	2,900	2,249	10.0
Magnesium (Mg^{2+})	99	50	56	0.42
Potassium (K^{+})	499	299	224	0.51
Sodium (Na^{+})	199	50	56	0.11

Note: Conversion to millequivalents:
lb Ca/acre divided by 400 = meq Ca/100 g
lb Mg/acre divided by 240 = meq Mg/100 g
lb Na/acre divided by 460 = meq Na/100 g
lb K/acre divided by 780 = meq K/100 g

Micronutrient	ppm (mg/kg)	lb/acre	kg/ha	mmol/kg
Boron	0.20	0.40	0.45	0.0185
Chlorine	19.9	20.9	22.4	0.282
Copper	0.12	0.24	0.27	0.0019
Iron	11.1	22.2	24.8	0.198
Manganese	0.55	1.10	1.23	0.010
Molybdenum	0.01	0.02	0.022	0.0001
Zinc	0.33	0.66	0.74	0.095

Note: Levels chosen for illustrative purposes only.

TABLE 13.10
Plant Analysis Values

Major Element	Percent	g/kg	cmol(p+)/kg	cmol/kg
Nitrogen	3.15	31.5	225	225
Phosphorus	9.32	3.2	—	—
Potassium	1.95	19.50	50	50
Calcium	2.00	20.00	25	50
Magnesium	9.48	4.80	10	20
Sulfur	0.32	3.29	10	20
Micronutrient	**ppm**	**mg/kg**	**cmol(p+)/kg**	**mmol/kg**
Boron	20	20	—	1.85
Copper	12	12	0.09	1.85
Iron	111	111	0.66	1.98
Manganese	55	55	0.50	1.00
Zinc	33	33	0.25	0.50

Note: Levels chosen for illustrative purposes only.

TABLE 13.11
Calculation of Millequivalents (meq) and Microequivalents (p.e.) per 100 g from Percent (%) and Parts per Million (ppm)

Element	Converting from	Valence	Equivalent Weight	Factor
Nitrogen	% to meq.	3	4.6693	214.6
Phosphorus	% to meq.	5	6.1969	161.39
Potassium	% to meq.	1	39.996	25.578
Calcium	% to meq.	2	29.049	49.990
Magnesium	% to meq.	2	12.169	82.237
Boron	ppm to p.e.	3	3.6967	27.726
Copper	ppm to p.e.	2	31.779	3.1476
Iron	ppm to p.e.	3	18.617	5.3726
Manganese	ppm to p.e.	2	27.465	3.6410
Zinc	ppm to p.e.	2	32.999	3.0590
Sulfur	% to meq.	2	16.933	62.377
Sodium	% to meq.	1	22.991	43.496
Chlorine	% to meq.	1	35.457	28.175

Note: Millequivalents can be converted to percentages by multiplying by equivalent weight/1000. Microequivalents can be converted to ppm by multiplying by equivalent weight/100. Factor x % = meq/100 g, and factor x ppm = p.e./100 g.

Appendix A
Soil/Plant Definitions

A

AB-DTPA Extraction Reagent An acronym for an extraction reagent of 1 *M* ammonium bicarbonate (NH_4HCO_3) in 0.005 *M* diethylenetriaminepentatacetic acid (DTPA) that has a pH of 7.6 and is used for the extraction of phosphorus (P), potassium (K), sodium (Na), iron (Fe), manganese (Mn), and zinc (Zn) from alkaline soils.

Absorption A process in which a substance is taken into something, such as a plant cell or structure, by either an active (biological) or passive (physical or chemical) process.

Acid-Forming Fertilizer Fertilizer that, after application to and reaction with soil, increases residual acidity and decreases soil pH.

Acid Soil A soil with a water pH below 7.0. A soil having a prepoderance of hydrogen (H^+) over hydroxyl (OH^-) ions in the soil solution.

Acidic Cations Hydrogen ions or cations that, on being added to ater, undergo hydrolysis resulting in an acidic solution. Examples in soils are: H^+, Al^{3+}, and Fe^{3+}.

Acidity Refers to the pH of a soil or solution in which the hydrogen (H^+) ion concentration exceeds that of the hydroxyl (OH^-) ion concentration, and therefore, the pH value is less than 7.0 (*see* Alkalinity).

Acidity, total The total acidity in a soil or clay, usually estimated by a buffered salt determination of total acidity, and also approximated by the sum of salt replaceable acidity plus residual acidity.

Adams-Evans Buffer A buffer solution used for measuring exchangeable hydrogen (H^+) and determining the lime requirement (LR) for acid, low cation exchange capacity (CEC) soils (*see* SMP Buffer).

Adsorption The attachment of a substance to the surface of another substance.

Aggregate A group of soil particles cohering so as to behave mechanically as a unit.

Aggreation The process whereby primary soil particles (sand, silt, clay) are bonded together, usually by natural forces and substances derived from root exudates and microbial activity.

AgLime (agricultural limestone) Refers to calcitic or dolomitic limestone that has been crushed to a certain fineness making it capable of neutralizing soil acidty.

Agronomy The branch of agriculture that deals with the theory and practice of field-crop production and soil management.

Air-dry The state of dryness at equilibrium with the water content in the surrounding atmosphere.

Alkaline Soil A soil with a water pH above 7.0. A soil having a preponderance of hydroxyl (OH^-) over hydrogen (H^+) ions in the soil solution.

Alkalinity Refers to the pH of a soil or solution in which the hydroxyl ion (OH^-) concentration exceeds that of hydrogen ion (H^+) concentration, and therefore, the pH value is greater than 7.0 (*see* Acidity).

Amino Acid An organic acid containing an amino group (NH_2), a carboxyl group (COOH), and an attached alkyl or aryl group.

Ammonium A cation consisting of one nitrogen (N) and four hydrogen (H) atoms to form a cation whose formula is NH_4^+. The ammonium (NH_4^+) cation exists in the soil solution and on the soil's cation exchange complex and is combined with various anions to form N fertilizer sources.

Anaerobic The absence of molecular oxygen (O_2).

Anion An ion in solution having a negative charge. In chemical notation, the minus sign indicates the number of electrons the compound will give up.

Anion Exchange Capacity The sum total of exchangeable anions that a soil can adsorb, and expressed as centimoles of charge per kilogram of soil.

Atom The smallest unit of a substance that cannot be broken down further or changed to another substance by purely chemical means.

Atomic Weight The average mass of a single atom of an element, expressed in terms of a dimensionless unit approximately equal to the mass of one hydrogen (H) atom.

Atmospheric Demand The capacity of air surtounding the plant to absorb moisture. This capacity of the air will influence the amount of water transpired by the plant through its exposed surfaces. Atmospheric demand varies with changing atmospheric conditions. It is greatest when air temperature and movement are high, and relative humidity is low. The reverse conditions exist when the atmospheric demand is low.

Available Nutrient Element in Soil A part of the supply of a plant nutrient element in soil that can be taken up by plants in amounts significant to plant growth.

Availability A term used to indicate that an element is in a form and position suitable for plant root absorption.

B

Banding A method of fertilizer applications.

Base Any compound that dissociates upon contact with water, releasing hydroxide (OH^-) ions.

Base Saturation Percentage Refers to the percentage of the cation exchange capacity (CEC) of the soil colloids by the cations calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+).

Basic Slag A by-product in the manufacturer of steel, containing lime, phosphorus (P), and small amounts of other plant nutrients, such as sulfur (S), manganese (Mn), and iron (Fe).

Beneficial Elements Elements not essential for plants but when present for plant use at specific concentrations enhance plant growth.

Boron (B) An essential element classified as a micronutrient involved in energy transfer and carbohydrate movement. The element exists in the plant and soil solution as the borate anion (BO_3^{3-}).

Bray P1 Extraction Reagent An extraction reagent of 0.03*N* ammonium fluoride (NH_4F) in 0.025 *N* hydrochloric acid (HCl) for determining soil-extractable phosphorus (P) in acid soils of moderate cation exchange capacity (CEC).

Bray P2 Extraction Reagent An extraction reagent of 0.03*N* ammonium fluoride (NH_4F) in 0.1 *N* hydrochloric acid (HCl) for determining soil-extractable phosphorus (P) in acid soils of moderate cation exchange capacity (CEC) that have been either fertilized with rock phosphate or that have sizable content of calcium phosphate.

Buffer Capacity A measure of the ability to maintain a constant pH by neutralizing excess acids or bases.

Buffer pH (pH_B) pH of soil in a buffer solution that can be used to measure exchangeable hydrogen ions (H^+) and calculate the lime requirement (LR) (*see* Adams-Evans Buffer and SMP Buffer).

Bulk Density The ratio of the mass of water-free soil to its bulk volume. When expressed in grams per cubic centimeter, bulk density in numerically equal to appear specific gravity or volume weight.

C

Calcareous Soil A soil having a pH above 7.0 that effervesces when a drop of 6 *M* hydrochloric acid (HCl) is placed on it.

Calcitic Limestone Mainly calcium carbonate ($CaCO_3$) finely ground and applied to soil to neutralize soil acidity.

Calcium Carbonate Equivalent (CCE) An expression of the neutralizing capacity of a liming material relative to pure calcium carbonate ($CaCO_3$), which is 100%.

Calcium (Ca) An essential element classified as a major element which serves as a specific component of organic compounds and exists in the soil solution as a cation (Ca^{2+}).

Catalyst A substance whose presence causes or speeds up a chernical reaction between two or more other substances.

Cation An ion having a positive charge. In chemical notation, the plus sign indicates the number of electrons the element will accept.

Cation Exchange The interchange among cations in the soil solution with other cations taking place on the surface of any surface-active colloidal material, such as clay or humus.

Cation Exchange Capacity (CEC) The total negative charge of colloidal clay and humus in soil measured in terms of exchange cation concentration in millequivalent per 100 grams (meq/100 g) of soil.

Chelate A type of chemical compound in which a metallic atom [such as iron (Fe)] is firmly combined with a molecule by means of multiple chemical bonds. The term refers to the claw of a crab, illustrative of the way in which the atom is held.

Chlorine (Cl) An essential element classified as a micronutrient which is involved in the evolution of oxygen (O) in photosystem II and raises cell osmotic pressure. Chlorine exists in the plant and soil solution as the chloride anion (Cl^-).

Chlorite A layer-structured group of silicate minerals of the 2:1 type that has the interlayer filled with a positively charged metal-hydroxide octahedral sheet.

Chlorophyll A complex molecule found in green plants that is directly involved in photosynthesis.

Chlorosis A light green to yellow coloration of leaves or whole plants which usually indicates an essential element insufficiency or toxicity.

Clay A soil particle (crystalline inorganic substances) less than 0.002 millimeter in diameter.

Coarse Texture The texture exhibited by sands, loamy sands, and sandy loams except very fine sandy loam.

Colloid A material that has been subdivided into extremely small particles capable of forming a colloidal suspension, particle size smaller than 0.001 millimeters (0.00004 inches) in diameter.

Conductivity A measure of the electrical resistance of a soil–water extract, or irrigation water, used to determine the level of ions in solution. Conductivity may be expressed as specific conductance as mhos/cm (micro- or milli-) or decisiemans/m (dS/m) (*see* Specific Conductance).

Consistence The attributes of soil material as expressed in its degree of cohesion and adhesion or in its resistance to deformation or rupture.

Copper (Cu) An essential element classified as a micronutrient which participates in electron transport, and protein and carbohydrate metabolism. Copper exists in the plant and soil solution as the cupric cation (Cu^{2+}).

Critical Nutrient Concentration/Value The nutrient concentration in the plant, or specified plant part, below which the nutrient becomes deficient for optimum growth rate.

D

Deficiency Describes the condition in which an essential element is not in sufficient supply or proper form to adequately supply the plant, or not in sufficient concentration in the plant to meet the plant's physiological requirement. Plants usually grow poorly and show visual signs of abnormality in color and structure.

Deflocculate To separate the individual components of compound particles by chemical and/or physical means, and to cause the particles of the disperse phase of a collodial system to become suspended in the dispersion medium.

Denitrification The conversion of organic or inorganic fixed nitrogen (N) to nitrogen (N_2) gas by either microbial activity or chemical reactions.

Diffusion The movement of an ion in solution at high concentration to an area of lower concentration. Movement continues as long as the concentration gradient exists.

Dolomitic Limestone Limestone that contains magnesium carbonate ($MgCO_3$), which may range from 4.4 to 22.6%. Pure dolimite is 54.3% calcium carbonate ($CaCO_3$) and 45.7% $MgCO_3$.

Drip Irrigation Irrigation whereby water is slowly applied to the soil surface through emitters that have small orifices.

DRIS An acronym for the Diagnosis and Recommendation Integrated System developed by Beaufils in 1973, which is based on nutrient relationships comparing an observed value to a corresponding ratio.

E

EC Acronym designating the electrical conductivity (EC) of a liquid or an extract from a soil, normally expressed in units of Siemens per meter (S/m) at 25°C.

Effective Calcium Carbonate Equivalent (ECCE) An expression of AgLime effectiveness based on the combined effect of chemical purity (CCE) and fineness. Other similar terms are effective neutralizing power (ENP), total neutralizing power (TNP), and effective neutralizing material (ENM).

Electron A tiny charged particle, smallest of the three principle constituents of the atom, with a mass of 9.1×10^{-28} grams and a negative charge of 1.6×10^{-19} coulomb.

Element A substance made up entirely of the same kind of atom.

Enzyme An organic compound that serves as a catalyst in metabolic reactions. Enzymes are complex proteins that are highly specific to particular reactions.

Essential Elements Those elements that are necessary for higher plants to complete their life cycle. Also refers to the requirements established for essentiality by Arnon and Stout in 1939.

Evaporation The conversion of a substance from the liquid state to the gaseous state. Evaporation occurs when a molecule of liquid gains sufficient energy (in the form of heat) to escape from the liquid into the atmosphere above it.

Evapotranspiration The sum of evaporation and transpiration which varies with temperature, wind speed, type of vegetation, and relative humidity.

Exchange Capacity The total ionic charge of the adsorption complex active in the adsorption of ions.

Exchangeable Acidity Titratable acidity removed from strongly acid soils by a neutral, unbuffered salt solution.

Exchangeable Anion A negatively charged ion held on or near the surface of a solid particle by a positive surface charge and which may be replaced by other negatively charged ions.

Exchangeable Cation A positively charged ion held on or near the surface of a solid by a negatice surface charge of a colloid and which may be replaced by other positively charged ions in the soil solution.

Exchangeable Cation Percentage The extent to which the adsorption complex of a soil is occupied by a particular cation: ECP = exchangeable cation/cation exchange capacity x 100.

Extractable Elements Those elements removed from the soil or dried plant tissue by means of an extraction reagent.

Exchangeable Ions Ions held on the soil complex that may be replaced by other ions of like charge. Ions which are held so tightly that they cannot be exchanged are called nonexchangeable.

Extraction Reagent A reagent that may be pure water, a mixture of acids, or buffered salts used to extract elements as ions from soil or plant tissue.

F

Fertilizer A substance added to the soil/plant system to aid plant growth or increase productivity by providing extra nutrient elements for plant use.

Fertilizer Analysis The present composition of a fertilizer as determined in a laboratory and expresed as total nitrogen (N), available phosphoric acid (P_2O_5), and water-soluble potash (K_2O).

Fertilizer Grade An expression that indicates the weight percentage of plant nutrient elements in a fertilizer; thus a 10–20–10 grade contains 10 percent nitrogen (N), 20 percent phosphate (P_2O_5), and 10 percent potash (K_2O).

Fertilizer Ratio The relative proportion of primary nutrient elements in a fertilizer grade divided by the highest common divisor for that grade; e.g., grades 10–6–4 and 20–12–8 have the ratio of 5–3–2.

Fertilizer Requirement The quantity of fertilizer needed to supply the difference between the nutrient element requirement of the crop and the nutrient element supplied by the soil.

Fertilizer Salt Index The ratio of the decrease in osmotic potential of a solution containing a fertilizer compound or mixture to that produced by the same weight of sodium nitrate ($NaNO_3$) x 100.

Fibrous Root System A plant root system consisting of a thick mat containing many short, slender, interwoven roots, without the presence of a taproot.

Fine Texture Consisting of or containing large quantities of the fine fractions, particularly of silt and clay.

Foliar Analysis An estimation of mineral nutrient deficiencies (excesses) of plants based on examination of the chemical composition of selected plant parts, and the color and growth characteristics of the foliage of the plants (*see* Leaf Analysis and Plant Analysis).

Foliar Fertilization Supplying plant nutrient elements directly to plant foliage with absorption taking place through the stomata of the leaves and leaf cuticle.

Free Space That portion, about 10%, of plant roots into which ions in the soil solution can passively enter the root without passing through a membrane.

G

Gibbsite Aluminum hydroxide [$Al(OH)_3$]. A mineral with a platy habit that occurs in highly weathered soils and in laterite.

Gram A unit of mass in the metric system, equivalent to the mass of one cubic centimeter of water at maximum density (4°C). There are 453.6 grams in an English pound.

Great Soil Group One of the categories in the system of soil classification that has been used in the United States. Great groups place soils according to soil moisture and temperature, base saturation status, and expression of horizons.

Gypsum Common name for calcium sulfate ($CaSO_4 \cdot 2H_2O$), used for reclaiming alkali soils, and improving soil physical characteristics, and a source for sulfur (S), as calcium sulfate contains approximately 18% S. Another common name is *landplaster.*

H

Halloysite A member of the kaolin subgroup of clay minerals.

Heavy Metals A group of metallic elements with relatively high atomic weights (>55) that generally have similar effects on biological functions. Elements such as cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), nickel (Ni), and mercury (Hg) are frequently identified as heavy metals, as well as the micronutrients copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn).

Humic Acid The dark-colored organic material that can be extracted from soil by various reagents (e.g., dilute alkali) and that is precipitated by acidification to pH 1 to 2.

Humidity The amount of water vapor in the air. Relative humidity is the ratio of the air's actual water content to the total amount of water vapor the same volume of air could theoretically hold under its current conditions of temperature and pressure.

Humus Organic materials within the soil that have been partially decomposed, forming a relatively stable organic matrix that has colloidal properties and, in turn, has a marked affect on the physical and chemical properties of a soil.

Hybrid An organism whose male and female parents are members of two separate and distinct genetic lines.

Hydrocarbon Any compound that contains only hydrogen (H), oxygen (O), and carbon (C) in its molecular structure.

Hydrogen Bond An electrostatic bond between an atom of hydrogen (H) in one molecule and an atom of another element in a neighboring molecule.

Hydroponics A method of growing plants without soil in which the essential elements are supplied by means of a nutrient solution that periodically bathes the plant roots.

Hydroscopic Capable of taking up moisture from the air.

Hydroxide Any inorganic compound containing hydrogen (H) and oxygen (O) bound together in the form of a negatively charged ion (OH-).

I

Illite The mica component of a structurally mixed fine grained mica and smectite or vermiculite.

Ion An atom that has lost or gained one or more electrons and has thus acquired a small positive or negative charge.

Ion Carriers A proposed theory that explains how ions are transported from the surface of a root into root cells, the transport being across a membrane and a concentration gradient, the transport occurring by means of a carrier or carriers.

Ion Exchange Refers to the phenomenon of physical–chemical attraction between charged colloidal substances (such as clay and humus) with cations and anions.

Ion Pumps A proposed theory that explains how ions are transported from the surface of a root into root cells, the transport being across a membrane and a concentration gradient

Iron (Fe) An essential element classified as a micronutrient which is involved in the electronic transport systems in plants. Iron can exist as either the ferrous (Fe^{2+}) or ferric (Fe^{3+}) cation in the plant or soil solution.

Irrigation The intentional application of water to the soil.

K

Kaolin A subgroup name of aluminum silicates with a 1:1 layer structure.

Kaolinite A clay mineral of the kaolin subgroup which has a general formula of $Al_2Si_2O_5(OH)_4$, and 1:1 layer structure.

Kriging A method based on the theory of regionalized variables for predicting without bias and minimum variance the spatial distribution of earth components, including soil properties.

L

Labile Pool The sum of an element in the soil solution and the amount of that element readily solubilized or exchanged when the soil is equilibrated with a salt solution.

Landplaster *see* Gypsum.

Leaching The removal of materials in solution from the soil.

Leaf Analysis A method of determining the total elemental content of a leaf and relating this concentration to the well-being of the plant in terms of its elemental composition (*see* Foliar Analysis and Plant Analysis).

Lignin A complex organic compound found as a constituent of the walls of plant cells.

Lime A term that generally refers to agricultural lime, as either ground limestone (calcium carbonate), hydrated lime (calcium hydroxide), or burned lime (calcium oxide), although it strictly refers to calcium oxide (CaO).

Lime Requirement (LR) The amount of AgLime (agricultural limestone, either calcitic or dolomitic) required to neutralize soil acidity by raising an acid soil to a higher pH level.

Loam The textural class name for soil having a moderate amount of all three soil seperates, sand, silt, and clay.

Luxury Consumption The uptake by a plant of an essential element in excess of its actual need.

M

Macronutrients *see* Major Essential Elements.

Magnesium (Mg) An essential element classified as a major element which is a constituent of the chlorophyll molecule and serves as an enzyme cofactor for phosphorylation processes. Magnesium exists in the plant and soil solution as a cation (Mg^{2+}).

Major Essential Elements The nine essential elements found in relatively large concentrations (>500 mg/kg) in mature plant tissues. These elements are: calcium (Ca), carbon (C), hydrogen (H), oxygen (O), magnesium (Mg), nitrogen (N), phosphorus (P), potassium (K), and sulfur (S).

Manganese (Mn) An essential element classified as a micronutrient which is involved in the oxidation-reduction processes and enzyme activator. Manganese exists in the plant and soil solution as a cation in several oxidation states (Mn^{2+}, Mn^{3+}, Mn^{4+}). The most common oxidation state is Mn^{2+}.

Manure The excreta of animals, with or without an admixture of bedding or litter, fresh or at various stages of further decomposition or composting, which can be used as fertilizer.

Marl Soft and unconsolidated calcium carbonates, usually mixed with varying amounts of clay or other impurities.

Mass Flow The movement of ions in soil as a result of the flow of water.

Mechanical Analysis Technique for the determination of the percent of sand, silt, and clay in a soil sample to identify its textural class.

Mehlich Buffer A buffer method for determining exchangeable acidity and the lime requirement (LR) for both mineral and organic soils.

Mehlich No. 1 Extraction Reagent An extraction reagent of 0.05*N* hydrochloric acid (HCl) in 0.025 *N* sulfuric acid (H_2SO_4) for extracting phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), and zinc (Zn) from acid sandy soils of low cation exchange capacity (CEC) and low organic matter (OM) content.

Mehlich No. 3 Extraction Reagent An extraction reagent of 0.2*N* acetic acid (CH_3COOH) + 0.015 *N* ammonium fluoride (NH_4F) + 0.25*N* ammonium nitrate (NH_4NO_3) + 0.013*N* nitric acid (HNO_3) + 0.001*M* EDTA for extracting phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), boron (B), and zinc (Zn) from acid to neutral pH soils.

Metabolism The set of chemical reactions taking place within the living cell that allows energy to be used and transferred and tissues to be constructed and repaired.

Metal Any element that has a positive valence, that is, one that gives up electrons when forming ionic compounds.

Mica A layer-structured aluminosilicate mineral group of the 2:1 type that is characterized by its high layer charge, which is usually satisfied by potassium (K).

Micronutrient Seven essential elements found in relatively small concentrations (< 100 mg/kg) in plant tissue. These elements are boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) (*see* Trace Elements).

Mineral A term used to identify an essential element.

Mineral Nutrition The study of the essential elements as they relate to the growth and the well-being of plants.

Mineral Soil A soil consisting predominantly of, and having its properties determined predominantly by, mineral matter.

Molecular Weight The weight of one molecule, ion, group, or other formula unit. The molecular weight is the sum of the atomic weights of the atoms that combine to make up the formula unit.

Molecule The smallest unit that a compound may be divided into and still retain its physical and chemical characteristics.

Molybdenum (Mo) An essential element classified as a micronutrient which is a component of two enzyme systems that are involved in the conversion of nitrate (NO_3) to ammonium (NH_4).

Montimorrillonite An aluminum silicate (smectite) with a layer structure composed of two silica tetrahdral sheets and a shared aluminum (Al) and magnesium (Mg) octahedral sheet.

Morgan Extraction Reagent An extraction reagent of 0.7*N* sodium acetate ($NaC_2H_3O_2$) and 0.54 *N* acetic acid (CH_3COOH) buffered at pH 4.8 for determining soil-extractable phosphorus (P), potassum (K), calcium (Ca), and magnesium (Mg) in acid soils of moderate cation exchange capacity (CEC) (*see* Wolf Modification).

Muriate of Potash Potassium chloride (KCl).

N

Neutral Soil A soil in which the surface layer, at least in the tillage zone, is in the pH 6.6 to 7.3 range.

Nitrate An anion of one atom of nitrogen (N) and three of oxygen (O) to form NO_3, which is a common form of N found in soils and that can be readily absorbed by plant roots in order to satisfy the N requirement of a plant.

Nitrification The formation of nitrate (NO_3) and nitrite (NO_2) from ammonium (NH_4) by soil microorganisms.

Nitrite An anion of one atom of nitrogen (N) and two of oxygen (O) to form NO_2, a reduced form of N that exists mostly under anaerobic conditions and is a form of N that is highly toxic to plants.

Nitrogen (N) An essential element classified as a major element which is a component of amino acids and proteins. Nitrogen exists in the atmosphere as a gas, and in the plant and soil solution as either the nitrate (NO_3^-) anion or the ammonium (NH_4^+) cation.

Nitrogen Fixing Bacteria Any of several genera of bacteria that have the ability to convert atmospheric nitrogen (N_2) into ammonium (NH_4) and nitrate (NO_3), which can then be used by other organisms.

Nutrient Element In plant nutrition use, refers to one of the essential elements and is frequently refered to as nutrient.

O

Olsen Extraction Reagent An extraction reagent of 0.5 *N* sodium bicarbonate ($NaHCO_3$) at pH 8.5 for determining phosphorus (P) in primarily alkaline soils.

Organic Matter Material that was formed by the bodily processes of an organism and as plant residues. Decaying organic matter (plant and organism residues) can be a source of essential plant nutrient elements, primarily nitrogen (N), phosphorus (P), sulfur (S), and boron (B).

Organic Soil A soil which contains a high percentage (>200 g/kg, or >120–180 g/kg if saturated with water) of organic carbon (C) throughout the solum.

Orthophosphate A molecular ion containing phosphorus (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$ depending on soil pH).

Osmosis The passage of water or another solvent through a membrane in response to differences in the concentrations of dissolved materials on opposite sides of the membrane.

Osmotic Pressure Force exerted by substances dissolved in water which affects water movement into and out of plant cells. Salts in the soil solution exert some degree of force which can restrict water movement into plant root cells or extract water from them.

Oven-Dried-Soil Soil that has been dried at 100°C until it reaches constant mass.

Oxygen (O_2) An essential element classified as a major element.

P

Parent Material The unconsolidated and more or less chemically weathered mineral or organic matter from which the solum or soils is developed by pedogenic processes.

Particle Density The density of the soil particles, the dry mass of the particles being divided by the solid (not bulk) volume of the particles, in contrast with bulk density. Units are mg/cm^3.

Particle Size The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods.

Parts per Million (ppm) Number of units by weight of a substance per million weight units of another.

Passive Absorption The movement of ions into plant roots carried along with water being absorbed by roots.

Percolation, Soil Water The downward movement of water through soil.

Petiole The stem of a leaf which connects the base of the leaf blade to the stem.

pH A measure of the acidity or basicity of a liquid; a measure of the number of hydrogen (H^+) ions present in the liquid (in moles/L), expressed as the negative logarithm. pH ranges from 1 (acid) to 10 (alkaline).

Phloem The tissue system of a vascular plant through which the sugar and other food substances formed in the leaves are conducted to other parts of the plant. The direction of flow is downward, the driving force being osmotic pressure.

Phosphorus (P) An essential element classified as a major element which is a component of several enzymes and proteins, and an element involved in various energy transfer systems in the plant. Phosphorus exists in the soil solution as an anion in various forms (PO_4^{3-}, HPO_4^{2+}, $H_2PO_4^{2-}$) depending on the soil pH.

Photosynthesis The synthesis of carbohydrates from carbon dioxide (CO_2) and water (H_2O) by living organisms utilizing light energy as an energy source which is catalyzed by chlorophyll according to the following formula: $6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$.

Plant Analysis A method of determining the total elemental content of the whole plant or one of its parts, and then relating the concentration found to the well-being of the plant in terms of its elemental requirement (*see* Foliar Analysis and Leaf Analysis).

Plant Nutrient Elements A term used to identify those elements that are essential to plants.

Plant Nutrient An element that is required by plants for normal growth and development.

Plant Nutrition The study of the effects of the essential as well as other elements on the growth and well-being of plants.

Plant Requirement That quantity of an essential element needed for the normal growth and development of the plant without inducing stress due to its deficiency or excess.

Porosity The volume of pores in a soil sample (nonsold volume) divided by the bulk volume of the sample.

Potash Designates potassium oxide (K_2O) content in a fertilizer.

Potassium (K) An essential element classified as a major element which maintains cellular turgor. Potassium exists in the plant and soil solution as a cation (K^+).

ppb An abbreviation for parts per billion, which is 1/1000 of a part per million, expressed in metric units as micrograms per kilogram (pg/kg) in weight units and micrograms per liter (µg/L) in liquid units.

ppm An abbreviation for parts per million, expressed in metric units as milligrams per kilogram (mg/kg) in weight units and milligrams per liter (mg/L) in liquid units.

R

Residual Fertility The available nutrient content of a soil carried over to subsequent crops.

Respiration The set of processes through which energy is obtained from sugars and other carbohydrates in the body of a living organism.

Rhizophere The zone of soil immediately adjacent to plant roots in which the kinds, numbers, or activities of microorganisms differ from that of the bulk soil.

Root Interception A concept of ion uptake by plant roots which is enhanced by the increased occupancy of the soil mass by roots and root characteristics.

S

Saline Soil A soil containing sufficient soluble salts to impair plant growth, having an electric conductivity (EC) greater than 4 dS/m in a saturation extract.

Saline/Sodic Soil A soil containing a sufficiently high combination of both salts and sodium (Na) to impair plant growth.

Salt Index An index used to compare solubilities of fertilizer compounds, usually based on the relationship with sodium nitrate ($NaNO_3$) which is set at 100.

Salt Tolerance The ability of plants to resist the adverse, nonspecific effects of excessive soluble salts in the rooting medium.

Salt pH Measurement of the soil water pH in a solution of either 0.01*M* calcium chloride ($CaCl_2$) or 1*N* potassium chloride (KCl).

Sand A soil particle between 0.05 and 2.0 mm in diameter.

Saturation Extract The solution extracted from soil at its saturation percentage.

Scorch Burned leaf margins, a visual symptom typical of potassium (K) deficiency or boron (B) and chloride (Cl) excess.

Separates Refers to three sizes of particles in soil: sand, silt, and clay (*see* Mechanical Analysis).

Silt A soil particle consisting of particles between 0.05 to 0.002 mm in equivalent diameter.

SMP Buffer A buffer solution used to measure exchangeable hydrogen ions (H^+) for determining the lime requirement (LR) of acid soil, with cation exchange capacities (CEC) greater than 10 meq/100 g (*see* Adams-Evans Buffer).

Sodic Soils A soil containing sufficient exchangeable sodium (Na) to affect its physiological properties and impair plant growth, usually having greater than 15% exchangeable cations.

Sodium Adsorption Ratio A ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with soil, expressed in milliequivalents per liter: $SAR = Na^+/(Ca^{2+} + Mg^{2+})^{1/2}/2$.

Soil Auger A tool for boring into the soil and withdrawing a small sample for field or laboratory observation.

Soil Characteristics Soil properties which can be described or measured by field or laboratory observations, e.g., color, temperature, water content, structure, pH, and exchangeable cations.

Soil Chemistry The branch of soil science that deals with the chemical constitution, chemical properties, and chemical reactions of soils.

Soil Extract The solution separated from soil suspension or from a soil by filtration, centrifugation, suction, or pressure.

Soil Horizon A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics such as color, structure, texture, consistency, kinds and number of organisms present, degree of acidity or alkalinity, etc.

Soil Organic Matter The organic fraction of the soil exclusive of undecayed plant and animal residue.

Soil Permeability Quality of soil that enables water or air to move through it.

Soil Profile A vertical section of the soil extending through all its horizons.

Soil pH A measure of the hydronium ion (H_3O^+) activity in the soil solution.

Soil Salinity The amount of soluble salts in a soil.

Soil Sample A representative sample taken from an area, a field, or portion of a field from which the physical and chemical properties can be determined.

Soil Science That science dealing with soils as a natural resource on the surface of the earth, including soil formation, classification and mapping, and physical, chemical, biological, and fertility properties of soils *per se*; and these properties in relation to their use and management.

Soil Separate One of individual-size groups of mineral soil particles, sand, silt, and clay.

Soil Series A group of soils that have soil horizons similar in their differentiating characteristics and arrangement in the soil profile, except for the texture of the surface soil, and that are formed from a particular type of parent material.

Soil Solution The liquid, water phase of the soil which contains solutes.

Soil Structure The physical arrangements of the soil particles.

Soil Test (Analysis) A series of analytical procedures used to determine the fertility status of a soil in terms of plant growth, and the need for lime and fertilizer additions.

Soil Test (Analysis) Calibration A two-stage pocedure to determine first the agronomic meaning of a soil test value (index) in terms of a particular crop response, and then to establish the amount of nutrient element(s) required for specific crops within each category to achieve optimum yield.

Soil Test (Analysis) Correlation A determination of the relationship between plant nutrient element uptake or yield, and the amount of nutrient element extracted by a soil test (analysis) procedure.

Soil Test (Analysis) Deficiency Critical Level That concentration of an extractable nutrient element below which deficiency occurs and above which sufficiency exists.

Soil Test (Analysis) Toxic Critical Level That concentration of an extractable nutrient element above which toxicity is likely to occur

Soil Test (Analysis) Value A nutrient element level expressed in either concentration or as an index value.

Soil Test Interpretation Category An interval of soil test (analysis) values associated with corresponding probabilities of response by a specific crop to a nutrient element application.

Soil Texture A method of soil calssification based on the precentage of sand, silt, and clay found in the soil (*see* Mechanical Analysis and Separates).

Soluble Salts Total soluble ions (anions and/or cations) in a soil and measured as the conductivity (EC) of a soil–water suspension or extract (*see* Conductivity).

Specific Conductance The reciprocal of the electrical resistance of a solution measured using a standard cell, expressed as mhos/cm (dS/m) at 25°C (77°F) (*see* Conductivity).

Standard Value The mean concentration of an element in plant tissue based on the analysis results from a large population of normal growing plants.

Sufficiency and Sufficiency Range The adequate supply of an essential element to the plant. Also, an adequate concentration of an essential element in the plant to satisfy the plant's physiological requirement. The plant in such a condition will look normal in appearance, be healthy and capable of high production.

Sulfur (S) An essential element classified as a major element which is a component of some proteins and is a component of glucosides that are the source for the characteristic odors of some plants. Sulfur exists in the plant and soil solution as the sulfate anion (SO_4^{2-}).

Surface Soil The uppermost part of the soil, ordinarily moved in tillage, or its equivalent in uncultivated soils and ranging in depth from 7 to 20 cm.

Symbiotic Bacteria Relates to bacteria that infect plant roots of legumes, forming nodules on the roots, fixing atmospheric nitrogen (N_2), thereby providing nitrogen (N) for the plant and obtaining their carbohydrates from the plant.

T

Tilth The physical condition of a soil with respect to its fitness for the growth of plants.

Tissue Testing A method for determining the concentration of the soluble form of an element in the plant by analyzing sap that has been physically extracted from a particular plant part, usually from stems or petioles. Tests are usually limited to the determination of nitrate (NO_3), phosphate (PO_4), potassium (K), and iron (Fe).

Topsoil The layer of soil moved in cultivation.

Toxicity The ability of a substance or element to disrupt the normal functions of a plant.

Trace Elements An obsolete term which was used to identify the micronutrients but today is used to identify those nonessential elements found in plant tissue in very low concentrations (*see* Micronutrients and Heavy Metals).

Tracking A technique of following through time the essential element content of the rooting media or plant by a sequence of analyses made at specified stages of plant growth.

Transpiration Loss of water vapor from leaves and stems of living plants to the atmosphere.
Tundra A level or undulating treeless plain characteristic of arctic regions.

V

Vermiculite A highly charged layer-structured silicate of the 2:1 type that is formed from mica.

W

Water Dihydrogen oxide (H_2O). Among the most familiar and ubiquitous of all chemicals, water is also among the most unusual, with a group of unique properties that place it in a class by itself. Water is highly polar, can exist as all three phases of matter—liquid, solid, and gaseous, has an extremely high surface tension, and is an excellent solvent.
Water pH (pHw) A measure of the hydrogen ion (H^+) concentration in the soil solution on a log scale from 0 to 14.
Water-Holding Capacity The weight of water held by a given quantity of absolutely dry soil when saturated.
Water Table The upper surface of ground water or that level in the ground where the water is at atmospheric pressure.
Wolf Modification The addition of diethylenetriaminepentaacetic acid (DTPA) to the Morgan extraction reagent to obtain the extractable micronutrients (*see* Morgan Extraction Reagent).

X

Xylem The tissue of a vascular plant through which water and minerals are transported upward from roots to the leaves.

Y

Yield The amount of a specified substance produced (e.g., grain, straw, total dry matter) per unit area.

Z

Zinc (Zn) An essential element classified as a micronutrient which is involved in several enzymatic functions in plants. Zinc exists in the plant and the soil solution as a cation (Zn^{2+}).

Appendix B
Botanical Definitions

Apical Situated at the tip of a stem.
Auricle Small lobe or ear; appendage to a leaf.
Awn Bristle-like appendage that form a beard on a plant.
Awned Having awns.
Axil Angle between the upper side of a leaf or stem and the supporting branch.
Chlorosis Loss of green color; plant tissue turns yellow or white; adjective is *chlorotic*.
Cotyledon Primary or rudimentary leaf of the embryo of a seed plant.
Dieback Deaths of leaves or growing buds; symptoms are not limited to single leaves or sections of leaves; they spread over the whole plants or leaves.
Glume Chaff-like bract in the spikelet of a grass.
Internode Area or part of a stem between two leaf nodes.
Interveinal Affecting only the tissue between the veins of a leaf.
Lamina Blade or flat surface of a leaf; attached to the stem directly or by a petiole.
Leaf base Section of a leaf nearest the point of attachment to the stem; opposite to the leaf tip.
Leaf tip Section of the leaf furthest from the point of attachment to the stem; opposite to the leaf base.
Leaflet Blade or separate division of a compound leaf.
Lesion Discrete or localized area of tissue that is chlorotic or necrotic, has distinct boundaries, and is surrounded by apparently healthy tissue.
Localized Symptom limited to one leaf or one section of a leaf or plant.
Marginal Localized symptom occurring on the margins of the lamina.
Meristem Growing tissue of small plant cell.
Mottling Blotchy pattern of indistinct light and dark (opaque and vitreous in grain) areas; irregularly spotted surface.
Necrosis Dead tissue; usually has brown, papery appearance; adjective is *necrotic*.
Petiole Stalk that attaches the leaf lamina to the stem.
Tiller Sucker or branch from the bottom of the stem.
Veins Vascular leaf bundles.
Weathertip Deaths of leaf tips or tips of ears or heads of cereals; they usually turn pale brown to white.
Wilting Condition of a plant when cells lack water and lose their turgidity; leaves, petioles, and stems droop.

Appendix C
Nutrient Element Requirements for Several Agronomic Crops (based on crop removal and/or growth response)

Agronomic Crop	Scientific Name	Major Element Requirement Levels					
		N	P	K	Ca	Mg	S
Barley	*Hordeum vulgare*	M	L	L	L	L	L
Cassava	*Manihot esculenta*	L	L	H	L	L	M
Corn, grain	*Zea mays*	H	M	M	M	M	M
Oat	*Avena sativa*	L	L	L	L	L	L
Peanut	*Arachis hypogaea*	M	L	L	H	L	M
Rice	*Oryza sativa*	L	L	L	L	VL	L
Rye	*Secale cereale*	L	VL	VL	(M)	(M)	L
Sorghum	*Sorghum bicolor*	H	M	M	L	M	M
Soybean	*Glycine max*	VH	M	M	M	L	M
Sugar beet	*Beta vulgaris*	H	L	VH	(M)	H	H
Wheat	*Triticum aestivum*	L	L	L	L	L	L

Micronutrient	Element	Requirement Levels				
		B	Cu	Fe	Mn	Zn
Barley	*Hordeum vulgare*	L	M	(M)	M	H
Cassava	*Manihot esculenta*	M	L	M	M	H
Corn, grain	*Zea mays*	L	(M)	H	(M)	(M)
Oat	*Avena sativa*	L	M	M	H	M
Peanut	*Arachis hypogaea*	L	H	H	M	M
Rice	*Oryza sativa*	L	L	M	H	M
Rye	*Secale cereale*	L	L	M	L	L
Sorghum	*Sorghum bicolor*	(L)	(M)	H	M	H
Soybean	*Glycine max*	L	M	M	M	H
Sugar beet	*Beta vulgaris*	M	L	M	H	M
Wheat	*Triticum aestivum*	L	M	L	M	L

VL = very low; L = low; M = medium; H = high; VH = very high. Requirements shown in parentheses designate levels assumed and not clearly known. If crop removal and/or growth response to an element are unknown, a medium (M) requirement is assumed. The only exception is boron (B), for which a low (L) requirement is always assumed.

Appendix D Troublesome Weeds

Weed spectra vary widely by crop and growing region. While some weeds flourish over wide geographic areas, local environmental conditions and production practices exert big impacts on weed populations, weed species, and degrees of difficulty of control. For example, a survey of corn from the Southern Weed Science Society's 12 states included 47 weeds. The list was narrowed to 10. Listed below are some of the most troublesome weeds most commonly cited by university weed-control specialists. They are listed in no particular order.

Southern corn	Midwest corn and soybeans	Southern soybeans	Southern cotton
Johnsongrass	Ragweed	Morning glory	Morning glory
Morning glory	Waterhemp	Sicklepod	Nutsedge
Broadleaf signalgrass	Canada thistle	Johnsongrass	Cocklebur
Texas panicum	Johnsongrass	Nutsedge	Bermudagrass
Sicklepod	Lambsquarters	Cocklebur	Velvetleaf
Cocklebur	Shattercane	Pigweed	Sicklepod
Pigweed	Hemp dogbane	Ragweed	Pigweed
Burcucumber	Foxtail	Bermudagrass	Spurge
Nutsedge	Velvetleaf	Lambsquarters	Palmer amaranth
Fall panicum	Cocklebur	Palmer amaranth	Prickly sida

Source: Troublesome weeds, *Progressive Farmer*, January 2002.

STEPS TO STOP RESISTANT WEEDS

- Scout fields before applying any herbicide to identify the weed species and to decide, based on economic levels, whether a herbicide application is necessary.
- Rotate crops with an accompanying rotation of herbicides with the same mode of action on the same field.
- Limit the number of applications of a single herbicide or a combination of herbicides with the same mode of action during a single growing season.
- Mix or sequentially treat using herbicides that each control the weeds in the fields but have different modes of action.
- Scout fields after application to detect weed escapes or shifts. If you find a potentially resistant weed or weed population, use available control methods to avoid seed deposition in the field.
- Clean equipment before leaving fields suspected of having resistant weeds.

Note: The Weed Science Society of America management guidelines.

Source: Steps to stop resistant weeds, *Progressive Farmer*, September 2002.

Appendix E
Legumes: Nutrient Element Deficiency Symptoms

Symptom	Deficient Element
Effects Spread throughout Plants or Confined to Older or Lower Leaves	
Generalized on whole plant; yellowing and drying or firing of lower leaves	
Light green plant; lower leaves affected first; other leaves soon follow; lower leaves fade to pale yellow, then brown; subsequent shedding; stunted growth due to lack of nitrogen fixation by bacteria	Nitrogen
Dark green plant; petioles and leaflets tilted upward; spindly, stunted plants; stems may turn red	Phosphorus
Light green plant; lower leaves die and drop prematurely	Molybdenum
Localized; mottling or chlorosis with or without leaf spots; little drying of lower leaves	
Areas between main veins become pale green; later turn deep yellow; bases and lower centers of leaves are not affected; deficiency appearing at a late stage of growth is shown by a downward curling of leaf margins, gradual yellowing from margins inward, and bronzing	Magnesium
Yellow mottling around the edges of leaves; chlorotic areas merge to form distinct, continuous yellow borders around tip ends and along sides of leaves that soon dry; dead tissue falls; leaves on small-leaved legumes tend to develop small white spots around the leaf margins first; stunted growth	Potassium
Brown spots and yellowing of leaf tissue develop between veins; dead tissue drops from chlorotic areas; stunted growth	Zinc
Effects Localized on Newer Leaves	
Stunted growth; terminal buds die following distortions at the tips or bases of young leaves	
Leaves yellowed and sometimes reddened near growing points; lower leaves remain healthy green color; internodes shorten and form rosettes; buds appear as white or light brown dead tissues; little flowering	Boron
Emergence of primary leaves delayed; emerged leaves are cup-shaped; primary leaves are necrotic; narrow chlorotic bands develop around remainder of leaves; terminal buds deteriorate; petioles break down	Calcium
Stunted growth; terminal buds remain alive	
Leaves turn light green to yellow; veins remain distinctly green; spots of dead tissue appear on leaves; heavy rains may cause chlorosis in young leaves to disappear	Manganese
Leaves turn yellow to almost white; principal veins remain green; spots of dead tissue appear, particularly at leaf margins; tissue drops away	Iron
Leaves including veins turn pale green to yellow; young leaves affected first	Sulfur
Young leaves wilt and wither without chlorosis; excessive leaf shedding	Copper

Appendix F
Characteristics of Essential Nutrient Elements

BORON (B)

Functions in Plants: A micronutrient associated with carbohydrate chemistry, B is believed to be important in the synthesis of uracil, a base for RNA formation and in cellular activities (division, differentiation, maturation, respiration, growth, etc.). Boron has long been associated with pollen germination and growth. It improves the stability of pollen tubes. It is relatively immobile in plants and is transported primarily in the xylem.

Content and Distribution: Boron requirements are separated by plant groups:

- Leaf content of monocots, 1 to 6 ppm B
- Dicots, 20 to 70 ppm B
- Dicots with latex systems, 80 to 100 ppm B

Boron tends to accumulate in leaf margins at concentrations 5 to 10 times those in leaf blades. Levels can increase enough to produce marginal burning and deaths of leaf margins. High Ca content creates a high B requirement; high K content accentuates the negative effects of low B tissue levels. B can exist in a plant as the borate (BO_3^{3-}) anion.

Movement in Soil and Plant Root Absorption: Boron moves in soil by mass flow and diffusion. Deficiency occurs when soil moisture levels are low for extended periods or after a long period of heavy rainfall that causes leaching.

Mobility: Immobile

Forms Utilized: Borate (BO_3^{3-}) anion and H_3BO_3 molecule.

Fertilizer Sources:

Source	Formula	% B
Boric acid	H_3BO_3	17
Fertilizer borate, 48	$Na_2B_4O_7 \cdot 10H_2O$	14–15
Fertilizer borate, granular	$Na_2B_4O_7 \cdot 10H_2O$	14
	$Ca_2B_6O_{11} \cdot 5H_2O$	10
Foliarel	$Na_2B_8O_{13} \cdot H_2O$	21
Solubor	$Na_2B_4O_7 \cdot 4H_2O + Na_2B_{10}O_{16} \cdot 10H_2O$	20
Borax	$Na_2B_4O_7 \cdot 10H_2O$	11

Hydroponic Reagent Sources:

Compound	Formula	% B
Boric acid	H_3BO_3	16
Solubor	$Na_2B_4O_7 \cdot 4H_2O + Na_2B_{10}O_{16} \cdot 10H_2O$	20

Concentration in Nutrient Solutions: 0.3 mg B/L (ppm).

Symptoms of Deficiency: Slowed and stunted new growth, with possible death of growing points and root tips (meristematic tissues); lack of fruit set and development; auxins accumulate at growing points; leaves and stems become brittle.

Symptoms of Excess: Leaf tips become yellow, followed by necrosis, as B accumulates in leaf margins; margins die; leaves assume a scorched appearance and fall prematurely.

Critical Level: 25 mg B/kg (ppm) in dry matter.

Reference Plant Content (Markert, 1994): 40 mg B/kg (ppm) in dry matter.

Available Forms for Plant Root Absorption: Most B in soil exists in organic plant and microorganism residues. Its release by residue decomposition serves as the major supply for crop utilization. It exists in the soil solution as the BO_3^{3-} anion, although recent findings suggest it can also exist as undissociated $B(OH)_3$. Since the major soil form is undissociated and neutral in charge, the primary loss of B from soils is by leaching. Leaching is also a common way to remove excess B from the surface soil and rooting zone.

Generally, total B in the soil can range from 20 to 200 ppm, while the amount available for absorption ranges from 1 to 5 ppm in the soil solution. The accepted range of B is narrow. A deficiency occurs when a hot water extract contains less than 1 ppm. Toxicity occurs at levels above 5 ppm. Boron availability is also influenced by soil water pH; the optimum range for maximum availability lies between 5.5 to 7.0.

Movement in Soil and Plant Root Absorption: Boron moves in soil by mass flow and diffusion, with deficiency occurring when soil moisture levels are low for extended periods, or after a long period of heavy, leaching rainfall.

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	B mg/kg (ppm) in Dry Matter
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	15–20
	10- to 30-cm bark sections from main stem just above the soil (14-month old plants)	33–40
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, prior to flowering)	30–80
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	9
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	30–75
Clover Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	15–50
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	30–80
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	25–50
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	25–50
Coastal Bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	6–30
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	5–15
	12 leaves below the whorl (prior to tasseling)	5–25
	12 ear leaves (initial silk)	4–25
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to intial bloom)	20–60
	25 vegetative stems (full bloom)	20–60
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	25–60
	25 whole tops (early pegging)	20–50
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	5–15
	25 mature leaves from new growth (panicle initiation)	6–10
Rye (*Secale cereale*)	25 whole tops (panicle initiation)	4–13

Plant (Scientific Name)	Plant Part (Time of Sampling)	B mg/kg (ppm) in Dry Matter
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 39-day old plants)	4–13
	25 mature leaves from new growth (37 to 56 days after planting)	1–10
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	1–10
	25 leaves, third leaf below head (grain in dough condition)	1–6
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	20–55
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 after planting)	31–200
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3 to 5 months after planting)	4–30
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	35–150
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	1–10
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	6–10

Toxic Level: >100 mg B/kg (ppm) in dry matter.

Major Antagonistic Elements: Ca, P, K, and N.

Major Synergistic Elements: P and N.

Agronomic Crops Susceptible to Deficiency: Alfalfa, clover, cotton, peanut, and sugar beet.

Soil Conditions for Deficiency: Acid sandy soils low in organic matter, overlimed soils, and organic soils.

Typical Concentration in Foliage of Normal Crops: 15 to 100 mg B/kg in dry matter, 0.2 to 1.3 mM cell sap content.

Concentration in Environment: 0.001 mol B per m^3.

Most Important Sources: Tourmaline, accessory in silicates and salts.

Usual Soil Content: 5 to 100 mg B/kg.

CALCIUM (Ca)

Functions in Plants: Calcium is a major element. It plays an important part in maintaining cell integrity and membrane permeability, enhances pollen germination and growth, and activates enzymes for cell mitosis, division, and elongation. Calcium may also be important for protein synthesis and carbohydrate transfer, and may detoxify heavy metals in plants.

Content and Distribution: Calcium content ranges from 0.20 to 5.00% of dry weight in leaf tissue, with sufficiency ranges from 0.30 to 3.00% in leaf tissue of most crops. Critical values vary considerably among various crop species and are lowest for grain crops and highest for some vegetable and most fruit crops. Highest concentrations are found in older leaves as the content in leaves tends to increase with age.

High-yielding crops contain from 10 to 175 lbs Ca per acre (11 to 196 kg per ha). Calcium removal is lower for grains and most fruit crops when only the grain or fruit is removed, leaving behind the plant which contains most of the Ca.

The relationship between Ca and K is as well known as the one between Ca and Mg. The ratios are used as DRIS norms for the interpretation of plant analysis results. The ratio of Ca to N in fruit crops and a similar ratio of Ca and B may be related to quality. Ammonium nutrition can create a Ca deficiency by reducing Ca uptake.

It has been suggested that total Ca content does not relate to sufficiency, since it accumulates in some plants as crystals of calcium oxalate. Extractable Ca (in 2% acetic acid) may be a better indicator of sufficiency. The critical concentration for soluble Ca is around 800 ppm, a concentation suggested as a true *critical* value for most plants.

It is generally assumed that if soil pH is within acceptable range in the rooting media, Ca should be of sufficient concentration to ensure sufficiency, assuming other factors are also within normal ranges. Soil pH seems to have little effect on Ca uptake.

Available Forms for Plant Root Absorption: Calcium exists as the Ca^{2+} cation in the soil solution and as exchangeable Ca on soil colloids. It is usually the cation of highest concentration in both soluble and exchangeable forms in high pH soils (>8.0), soils that may contain sizable quantities of Ca as precipitates of $CaCO_3$ and $CaSO_4$.

Movement in Soil and Plant Root Absorption: Calcium moves in the soil by mass flow, the dominant supply factor, and diffusion. Its availability can be significantly affected by soil moisture level. Reduced evapotranspiration will also reduce root uptake.

Mobility: Immobile

Form Utilized: Ca^{2+} cation

Calcium Liming and Fertilizer Sources:

Carrier	Formula	% Ca
	Liming Materials	
Blast furnace slag	$CaSiO_3$	29
Calcitic limestone	$CaCO_3$	32
Dolomitic limestone	$CaCO_3 + MgCO_3$	22
Hydrated lime	$Ca(OH)_2$	46
Precipitated lime	CaO	60
	Fertilizers	
Calcium nitrate	$Ca(NO_3)_2$	19
Superphosphate, normal	$Ca(H_2PO_4)_2 + CaSO_4{\cdot}2H_2O$	20
Superphosphate, triple	$Ca(H_2PO_4)_2$	14
	Others	
Gypsum	$CaSO_4{\cdot}2H_2O$	23
Gypsum (by-product)	$CaSO_4{\cdot}2H_2O$	17 (varies)
Gypsum (impure)	$CaSO_4{\cdot}2H_2O$	15 (varies)

For acid soils, it is assumed that maintaining pH within the optimum range (5.8 to 7.5) by frequent liming will provide sufficient Ca to meet crop requirements.

Hydroponic Reagent Sources:

Compound	Formula	% Ca
Calcium chloride	$CaCl_2$	36 (64% Cl)
Calcium nitrate	$Ca(NO_3)_2{\cdot}4H_2O$	19 (15% N)
Calcium sulfate	$CaSO_4{\cdot}2H_2O$	23 (19% S)

Concentration in Nutrient Solutions: 20 to 300 mg Ca/L (ppm).

Symptoms of Deficiency: The growing tips of roots and leaves turn brown and die, a symptom called *tipburn*. Leaves curl and their margins turn brown. Margins of emerging leaves stick together, leaving the expanded leaves with shredded edges. Fruit quality decreases and incidence of blossom-end rot and internal decay is high.

Since Ca is immobile in plants, deficiencies occur at growing terminals. Reproduction may be delayed or terminated. The conductive tissue at the bases of plants will decay. This reduces water intake, produces wilting on high atmospheric demand days, and reduces essential element uptake.

Symptoms of Excess: Excessive Ca will produce a deficiency of Mg or K, depending on Mg and K concentrations present.

Critical Level: 1.00% in dry matter (varies with plant type and growth stage).

Excessive Level: >5.00% in dry matter (varies with levels of K and/or Mg).

Reference Plant Content (Markert, 1994): 1.00% in dry matter.

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	Ca % in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	0.30–1.20
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	0.60–1.50
10- to	30-cm bark sections from main stem just above the soil (14-month old plants)	2.40–3.70
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, prior to flowering)	2.00–3.50
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	0.52
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	1.70–2.00
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	1.00–1.80
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	2.00–2.60
	Ladino/White (*Trifolium repens f. lodigense*) 50 mature leaves (prior to flowering)	0.50–1.00
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	1.00–1.50
Coastal bermudagrass (*Cynodon dactylon*)	40 whole 4- to 5-week old plants	0.25–0.50
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	0.21–1.00
	12 leaves below the whorl (prior to tasseling)	0.30–0.70
	12 ear leaves (initial silk)	0.25–0.50
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	2.00–3.00
	25 vegetative stems (full bloom)	2.20–3.50
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	0.20–0.50
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	1.25–2.00
	25 whole tops (early pegging)	1.25–1.75
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	0.15–0.30
	25 mature leaves from new growth (panicle initiation)	0.12–0.40
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- 39- day old plants)	0.90–1.30
	25 mature leaves from new growth (37–56 days after planting)	0.15–0.90
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	0.30–0.60
	25 leaves, third leaf below head (grain in dough condition)	0.20–0.60
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	0.35–2.00
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 after planting)	0.50–1.50
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	0.20–0.50
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	1.50–3.00
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	0.19–0.35
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	0.20–0.50
Winter wheat	50 leaves, top two leaves (just before heading)	0.20–1.00

Major Antagonistic Elements: Al, Ba, Be, B, Cd, Cs, Cr, Co, Cu, Fl, Fe, Pb, Li, Mn, Ni, Sr, and Zn.

Major Synergistic Elements: Cu, Mn, and Zn.

Most Important Sources: Feldspar, augite, hornblende, $CaCO_3$, and $CaSO_4$.

Usual Soil Content: 0.2 to 1.5% (except chalk soils).

CHLORINE (Cl)

Functions in Plants: Chlorine is a micronutrient involved in the evolution of O_2 in Photosystem II of the photosynthetic process. It raises cell osmotic pressure, affects stomatal regulation, and increases hydration of plant tissue. Chlorine may be related to the suppression of leaf spot disease in wheat and fungus root disease in oats.

Content and Distribution: The leaf content of Cl ranges from low levels (20 ppm) in dry matter to percent concentrations. A deficiency occurs in wheat when plant levels are below 0.15%. Cl exists in plants as the Cl^- anion.

Available Forms for Plant Root Absorption: Chlorine exists in the soil solution as the Cl^- anion which moves by mass flow. The anion competes for uptake with other anions, such as NO_3^- and SO_4^{2-}) for uptake.

Mobility: Mobile

Form Utilized by Plants: Cl^- anion.

Fertilizer Sources:

Source	Formula	% Cl
Potassium chloride	KCl	47

Trace amounts found in many fertilizers are usually sufficient to satisfy most crop requirements.

Hydroponic Reagent Sources:

Compound	Formula	% Cl
Calcium chloride	$CaCl_2$	63 (36% Ca)
Potassium chloride	KCl	47 (50% K)

Concentration in Nutrient Solutions: 50 to 1,000 mg Cl per L (ppm), depending on reagent used.

Symptoms of Deficiency: Deficient plants exhibit chlorosis of younger leaves and wilting. Deficiency is not common. Deficiencies in wheat and oats in some soil areas has been related to disease infestation.

Symptoms of Excess: An excess produces premature yellowing of leaves, burning of leaf tips and margins, bronzing, and abscission of leaves. Excess is primarily associated with salt-affected (high NaCl content) soils, a condition that influences the osmotic characteristics of roots by restricting the uptake of water and other ions.

Critical Level: 20 mg Cl per kg (ppm) in dry matter.

Sufficiency Range: 20 to 1,500 mg Cl per kg (ppm) in dry matter.

Excess Level: >0.50% in dry matter.

Reference Plant Content (Markert, 1994): 0.20% in dry matter.

Agronomic Crops Susceptible to Deficiency: Small grains.

Typical Concentration in Foliage of Normal Crops: 100 to 1,000 mg Cl per kg dry matter, 0.4 to 4.0 mM cell sap content.

Concentration in Environment: 0.001 mol Cl per m^3.

Usual Soil Content: 30 to 450 mg Cl per kg (extreme values: 5 to 800 mg Cl per kg).

COPPER (Cu)

Functions in Plants: Copper is a micronutrient, a constituent of the plastocyanin chloroplast protein, and a component of the electron transport system linking Photosystems I and II in the photosynthetic process. Copper participates in protein and carbohydrate metabolism and N_2 fixation. It is a component of enzymes that reduce atoms of molecular oxygen (cytochrome oxidase, ascorbic acid oxidase, and polyphenol oxidase) and is involved in the desaturation and hydroxylation of fatty acids.

Content and Distribution: Cu sufficiency range in leaves is 3 to 7 ppm of dry matter; toxicity range begins at 20 to 30 ppm. Much higher values, 20 to 200 ppm, can be tolerated if Cu is applied as a fungicide. Copper in plants can interfere with Fe metabolism and lead to Fe deficiency. In interactions with Mo, Cu may interfere with enzymatic reduction of NO_3.

Available Forms for Plant Root Absorption: Copper exists in the soil primarily in complexed forms as low molecular weight organic compounds such as humic and fulvic acids. The cupric (Cu^{2+}) cation is present in small quantities in the soil solution. Deficiency occurs primarily on sandy and organic soils. Uptake rates are lower than for most other micronutrients.

Movement in Soil and Plant Root Absorption: Although Cu supply in the soil solution is very low (<0.2 mg Cu per kg), most soils have sufficient Cu to meet crop requirements and are able to maintain sufficient Cu^{2+} cations in the soil solution even with increasing pH. However with increasing organic matter content, Cu availability can be significantly reduced.

Soil–Plant Transfer Coefficient: 0.1 to 10.

Mobility: Immobile.

Form Utilized: Cupric (Cu^{2+}) cation.

Fertilizer Sources:

Source	Formula	% Cu
Copper sulfate (monohydrate)	$CuSO_4·H_2O$	35
Copper sulfate (pentahydrate)	$CuSO_4·5H_2O$	25
Cupric oxide	CuO	75
Cuprous oxide	Cu_2O	89
Cupric ammonium phosphate	$Cu(NH_4)PO_4·H_2O$	32
Basic copper sulfates	$CuSO_4·3Cu(OH)_2$ (general formula)	13–53
Cupric chloride	$CuCl_2$	47
Copper chelates	$Na_2CuEDTA$	13
	NaCuHEDTA	9
Copper polyflavonoids	Organically bound Cu	5–7

Copper can be soil- or foliar-applied; some sources are shown in this table.

Hydroponic Reagent Sources:

Compound	Formula	% Cu
Copper sulfate	$CuSO_4{\cdot}5H_2O$	25 (13% S)
Copper sulfate (monohydrate)	$CuSO_4{\cdot}H_2O$	35 (18% S)
Copper chloride	$CuCl_2$	47
Copper chelates	$Na_2CuEDTA$	13
	NaCuHEDTA	9

Concentration in Nutrient Solutions: 0.01–0.1 mg Cu per L (ppm); highly toxic to roots in excess of 1.0 mg per L (ppm) in solution

Symptoms of Deficiency: Symptoms include stunted growth with distortion of young leaves and necrosis of the apical meristems. In trees, deficiency may cause white tips or bleaching of younger leaves and summer dieback.

Symptoms of Excess: Excess Cu can induce Fe deficiency and chlorosis. Root growth may be suppressed, with inhibited elongation and lateral root formation at relatively low Cu levels in the soil solution. Copper is 5 to 10 times more toxic to roots than Al and may more significantly affect root development into acid (pH <5.5) subsoils.

Critical Plant Level: 5 mg Cu per kg (ppm) in dry matter.

Toxic Plant Level: >50 mg Cu per kg (ppm) in dry matter.

Reference Plant Content (Markert, 1994): 10 mg Cu per kg (ppm) in dry matter.

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	Cu mg per kg (ppm) in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from the boot)	5–25
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	7–15
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	6–7
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, prior to flowering)	7–30
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	11
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	6–10
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	3–15
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	8–15
Ladino/White (Trifolium repens f. lodigense)	50 mature leaves (prior to flowering)	5–8
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	7–13
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	5–25
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	6–20
	12 leaves below whorl (prior to tasseling)	5–20
	12 ear leaves (initial silk)	3–15
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	5–25
	25 vegetative stems (full bloom)	5–25
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	5–25
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	5–20
	25 whole tops (early pegging)	10–50
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	8–25
	25 mature leaves from new growth (panicle initiation)	8–25

Plant (Scientific Name)	Plant Part (Time of Sampling)	Cu mg per kg (ppm) in Dry Matter
Rye (*Secale cereale*)	25 whole tops (panicle initiation)	8–15
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 29-day old plants)	8–15
	25 mature leaves from new growth (37–56 days after planting)	2–15
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	2–7
	25 leaves, third leaf below head (grain in dough condition)	1–3
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	10–30
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	5–15
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	4–25
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	7–45
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	5–25
Winter wheat	50 leaves, top two leaves (just before heading)	5–50

Relative Tolerance to Copper

Low	Moderate	High
Pasture grass, rice rye, soybean	Barley, corn, cotton, sorghum, sugar beet	Alfalfa, barley, Lucerne, millet, oat, pangola grass, Sudan grass, wheat

Major Antagonistic Elements: Ca, Mg, P, and N.
Major Synergistic Elements: Ca, P, and N.
Soil Conditions for Deficiency: Organic soils, mineral soils high in Cu and organic matter content.
Typical Concentration in Foliage of Normal Crops: 5 to 15 mg per kg in dry matter, 0.01 to 0.03 mM cell sap content.
Concentration in Environment: 3 x 10^{-4} mol Cu per m^3.
High Accumulator Crops: Sugar beets and some barley cultivars.
Most Important Sources: Copper sulfide, sulfate, and carbonate.
Usual Soil Content: 5 to 100 mg Cu per kg (extreme values: 0.1 to 1,300 mg Cu per kg).

IRON (Fe)

Functions in Plants: Iron is a micronutrient and an important component in many plant enzyme systems, such as cytochrome oxidase (electron transport) and cytochrome (terminal respiration step). Iron is a component of ferredoxin and is required for NO_3 and SO_4 reduction, N_2 assimilation, and energy (NADP) production. It functions as a catalyst or part of an enzyme system associated with chlorophyll formation and may be involved in protein synthesis and root-tip meristem growth. Its plant and soil chemistry is highly complex and both facets are under intensive study.

Content and Distribution: Leaf content ranges from 10 to 1,000 ppm in dry matter; sufficiency ranges from 50 to 75 ppm, although total Fe may not always be related to sufficiency. In general, 50 ppm is the accepted critical value for most crops, with deficiency likely when total leaf Fe is lower. An accurate determination of plant content is normally not possible since extraneous sources of Fe are difficult to exclude from the determination. Soil and dust contamination are the primary contributors to extraneous Iron. Decontamination (washing) procedures are described in Chapter 12.

Iron deficiency affects many crops. A common deficiency known as lime chlorosis appears on alkaline soils. Most plant Fe is in the Fe^{3+} form as ferric phosphoprotein, although the ferrous (Fe^{2+}) ion is believed to be metabolically active.

High P decreases the solubility of Fe in plants. A P:Fe ratio of 29:1 is average for most plants. K increases the mobility and solubility of Fe, while N accentuates Fe deficiency due to increased growth. The bicarbonate anion is believed to interfere with Fe uptake and translocation. High Zn can interfere with Fe metabolism and produce visual symptoms of Fe deficiency.

Extractable ferrous (Fe^{2+}) iron may be a better indicator of plant Fe status than total Fe. Various extraction procedures have been proposed for diagnosing Fe deficiency and 20 to 25 ppm appears to be the critical extractable Fe range. Most methods of determining Fe status by means of analysis, whether total or extractable, are flawed because of soil and dust particles on tissue and Fe added during plant tissue processing. The indirect measurement of chlorophyll content may be the best alternative method for Fe sufficiency diagnosis.

Available Forms for Plant Root Absorption: Iron exists in the soil as both the ferric (Fe^{3+}) and ferrous (Fe^{2+}) cations. The Fe^{2+} form, whose availability is affected by the degree of soil aeration, is thought to be the active form taken up by plants. Iron-sufficient plants can acidify the rhizosphere and release Fe-complexing substances, such as siderophores, which enhance Fe availability and uptake, while Fe-inefficient plants do not exhibit similar root characteristics.

Movement in Soil and Plant Root Absorption: Iron moves in the soil by mass flow and diffusion. When an Fe ion reaches the rhizosphere, it is reduced (from Fe^{3+} to Fe^{2+}), or released from a chelated form (although chelated Fe can also be taken into a plant), and absorbed. Copper, Mn, and Ca competitively inhibit Fe uptake, and high levels of P reduce Fe uptake.

Mobility: Immobile.

Forms Utilized by Plants: Ferrous (Fe^{2+}) and ferric (Fe^{3+}) cations.

Fertilizer Sources:

Source	Formula	% Fe
Ferrous ammonium phosphate	$Fe(NH_4)PO_4 \cdot H_2O$	29
Ferrous ammonium sulfate	$(NH_4)_2SO_4.FeSO_4 \cdot 6H_2O$	14
Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	19–21
Ferric sulfate	$Fe(SO_4)_3 \cdot 4H_2O$	23
Iron chelates	FeHEDTA	5–9
	FeEDDHA	6
	NaFeEDTA	5–11
	NaFeHFDTA	5–9
	NaFeEDDHA	6
	NaFeDTPA	10
Iron polyflavonoids	Organically bound Fe	9–10

Iron sources can be soil- or foliar-applied. Foliar application is the most efficient with a solution of $FeSO_4$ or one of the chelated (EDTA or EDDHA) forms.

Hydroponic Reagent Sources:

Compound	Formula	% Fe
Iron chelate	FeEDTA	~12
Iron citrate Iron tartrate	$FeC_4H_4O_6$	2.7
Iron lignin sulfonate		6
Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	20 (11% S)

Concentration in Nutrient Solutions: 2 to 12 mg Fe per L (ppm).

Symptoms of Deficiency: Interveinal chlorosis of younger leaves is a typical deficiency symptom. As the severity increases, chlorosis spreads to the older leaves.

Symptoms of Excess: Iron may accumulate to several hundred ppm without toxicity symptoms. At toxic levels (not clearly defined), bronzing of the leaves with tiny brown spots will appear, a typical symptom in rice.

Critical Level in Plants: 50 mg Fe per kg (ppm) in dry matter.

Reference Plant Content (Markert, 1994): 150 mg Fe per kg (ppm) in dry matter.

Sufficiency Ranges in Plants:

Plant (Scientific Name)	**Plant Part (Time of Sampling)**	**Fe mg per kg (ppm) in Dry Matter**
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	60–200
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	82–150
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, (prior to flowering)	30–250
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	100
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	50–100
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	30–250
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	50–100
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	50–200
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week-old plants)	50–350
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	20–250
	12 leaves below the whorl (prior to tasseling)	50–250
	12 ear leaves (initial silk)	50–200
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	50–250
	25 vegetative stems (full bloom)	40–300
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	40–150
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	60–300
	25 whole tops (early pegging)	100–250
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	75–200
	25 mature leaves from new growth (panicle initiation)	70–150
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 30-day-old plants)	160–250
	25 mature leaves from new growth (37–56 days after planting)	55–200
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	65–100
	25 leaves, third leaf below head (grain in dough condition)	40–80
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	50–350
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 after planting)	60–140
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	40–250
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	50–250
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	22–54
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	25–100
Winter wheat	50 leaves, top two leaves (just before heading)	10–300

Agronomic Crops Susceptible to Deficiency: Barley, peanuts, soybeans, sorghum, Sudan grass, and sugar beet.

Agronomic Crops Susceptible to Excess: Rice.

Major Antagonistic Elements: Ca, Mg, P, and S.

Major Synergistic Elements: P, N, and S.

Soil Conditions for Deficiency: Leached sandy soils low in organic matter, alkaline soils, soils high in P.

Typical Concentration in Foliage of Normal Crops: 50 to 300 mg Fe per kg dry matter, 0.15 to 0.75 mM cell sap content.

Concentration in Environment: 0.001 mol Fe per m^3.

Most Common Sources: Augite, hornblende, biotite, olivine, iron oxide, and hydroxide.

Usual Soil Content: 0.5 to 4.0% Fe (extreme values: 10 to 80,000 mg Fe per kg).

MAGNESIUM (Mg)

Functions in Plants: Magnesium is a major element and component of the chlorophyll molecule. It serves as a cofactor in most enzymes that activate phosphorylation as a bridge between pyrophosphate structures of ATP or ADP and enzyme molecules, and stabilizes ribosome particles in configurations for protein synthesis.

Content and Distribution: Plant content ranges from 0.15 to 1.00% of dry weight in leaf tissue. The sufficiency value is 0.25% in the leaf tissues of most crops. Critical values may vary among crop species. They are lowest for grain crops and highest for legumes, some vegetables, and fruit crops. The Mg content in leaves increases with age; the highest concentrations are found in older leaves. High yielding crops will contain 10 to 175 lb Mg per acre (11 to 196 kg Mg per ha), with crop removal considerably less for grain and some fruit crops when only the grain or fruit is removed, leaving behind most of the Mg that exists primarily in the plant.

The relationships of Mg and K and Mg and Ca are well known. The ratios are used as DRIS norms for the interpretation of plant analysis result. Magnesium deficiency can be induced by high concentrations of NH_4^+, K^+, or Ca^{2+} cations in the rooting medium. The Mg^{2+} cation is the poorest competitor among the cations. Some plant species and cultivars within species have particular sensitivities to Mg and will become Mg-deficient under moisture and/or temperature stress even though Mg may be at sufficient availability levels in the rooting media.

Available Forms for Plant Root Absorption: Magnesium exists as the Mg^{2+} cation in the soil solution and as exchangeable Mg on soil colloids. The cation usually has the next to the highest in concentration in the soil in both soluble and exchangeable forms when the soil is slightly acid to neutral. Manganese availability declines significantly when the soil water pH is below 5.4.

Movement in Soil and Plant Root Absorption: The supply of Mg to roots depends on root interception, mass flow, and diffusion. Mass flow is the primary delivery mechanism. Deficiency can occur under soil moisture stress even when the soil is adequate in available Mg.

Mobility: Moderately immobile.

Form Utilized by Plants: Magnesium (Mg^{2+}) cation.

Fertilizer Sources:

Source	Formula	Water Solubility	% Mg
Dolomitic limestone	$CaCO_3 + MgCO_3$	Insoluble	6–12
Kieserite (magnesium sulfate)	$MgSO_4{\cdot}H_2O$	Slightly soluble	18
Magnesium sulfate (Epsom salt)	$MgSO_4{\cdot}H_2O$	Soluble	10
Potassium magnesium sulfate	$K_2SO_4{\cdot}MgSO_4$	Soluble	11
Pro/Mesium	$3MgOSiO_2{\cdot}2H_2O$	Insoluble	22
Magnesium oxide	MgO	Slightly soluble	50–55

As for Ca, it is assumed that maintaining soil pH within the optimum range (5.8 to 7.5) in acid soils by frequent liming using dolomitic (Mg-bearing) limestone or other high-content liming materials will provide sufficient Mg to meet crop requirements.

Hydroponic Reagent Sources:

Compound	Formula	% Mg
Magnesium sulfate (Epsom salt)	$MgSO_4 \cdot 7H_2O$	10 (23% S)

Concentration in Nutrient Solutions: 30 to 50 mg Mg per L (ppm).

Symptoms of Deflciency: Deficient plants exhibit yellowing of leaves or interveinal chlorosis that begins on the older leaves since Mg is a mobile element. With an increased deficiency, symptoms appear on the younger leaves with the development of necrosis when the deficiency is very severe.

Symptoms of Excess: Manganese deficiency has no specific toxicity symptoms. The Mg content of a plant can be quite high (>1.0%) in leaf tissue without inducing a deficiency of Ca or K. However, an imbalance among these three elements when the Mg content is unusually high may reduce growth.

Critical Level in Plants: 0.25% in dry matter.

Reference Plant Content (Markert, 1994): 0.2% in dry matter .

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	Mg % in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	0.15–0.50
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	0.25–0.50
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	0.40–0.60
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, prior to flowering)	0.30–1.50
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	0.32
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	0.40–0.60
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	0.30–0.60
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	0.21–0.60
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	0.20–0.30
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	0.25–0.50
Coastal Bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	0.13–0.30
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	0.20–1.00
	12 leaves below whorl (prior to tasseling)	0.15–0.45
	12 ear leaves (initial silk)	0.13–0.30
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	0.30–0.90
	25 vegetative stems (full bloom)	0.30–0.80
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	0.15–0.50
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	0.30–0.80
	25 whole tops (early pegging)	0.30–0.80
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	0.15–0.30
	25 mature leaves from new growth (panicle initiation)	0.20–0.30

Plant (Scientific Name)	Plant Part (Time of Sampling)	Mg % in Dry Matter
Rye (*Secale cereale*)	25 whole tops (panicle initiation)	0.20–0.60
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 39-day old plants)	0.35–0.50
	25 mature leaves from new growth (37–56 days after planting)	0.20–0.50
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	0.10–0.20
	25 leaves, third leaf below head (grain in dough condition)	0.10–0.50
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	0.25–1.00
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 after planting)	0.25–1.00
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	0.10–0.35
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	0.25–1.00
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	0.16–0.25
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	0.15–0.50
Winter wheat	50 leaves, top two leaves (just before heading)	0.15–1.00

Excessive Plant Level: >1.50% Mg dry matter (may vary with level of K and/or Mg).
Major Antagonistic Elements: Al, Ba, Be, Cr, Co, Cu, F, Fe, Mn, Ni, and Zn.
Major Synergistic Elements: Al and Zn.
Most Important Sources: Augite, hornblende, olivine, biotite, and $MgCO_3$.
Usual Soil Content: 0.1 to 1.0% (except for dolomitic soils).

MANGANESE (Mn)

Functions in Plants: Manganese is a micronutrient. It is involved in the oxidation–reduction processes in the photosynthetic electron transport system. It is essential in Photosystem II for photolysis, and acts as a bridge for ATP, phosphokinase complexes, and phosphotransferases, and activates IAA oxidases.

Content and Distribution: Leaf sufficiency ranges from 10 to 50 ppm in dry matter in mature leaves. Tissue levels will reach 200 ppm or higher (soybean, 600; cotton, 700; sweet potato, 1,380) before severe toxicity symptoms develop.

Available Forms for Plant Root Absorption: Manganese exists in the soil solution as Mn^{2+}, Mn^{3+}, and Mn^{4+} cations and as exchangeable Mn. Manganese (Mn^{2+}) is the ionic form taken up by plants. Availability is significantly affected by soil pH, decreasing when the pH exceeds 6.2 in some soils, while in other soils, the decrease may not occur until the soil water pH reaches 7.5. Manganese availability can be reduced significantly by low soil temperatures. Soil organic matter can affect Mn availability, decreasing its availability with an increase in organic matter content.

Movement in Soil and Plant Root Absorption: Manganese is primarily supplied to plants by mass flow and root interception. Low soil temperature and moisture stress reduce Mn uptake. Some plants may release root exudates that reduce Mn^{4+} to Mn^{2+}, complex it, and thus increase Mn availability.

Mobility in Plants: Immobile.

Form Utilized by Plants: Manganous (Mn^{2+}) cation.

Fertilizer Sources:

Source	Formula	% Mn
Manganese sulfate	$MnSO_4{\cdot}4H_2O$	24 (14% S)
Manganese oxide	MnO	53
Manganese chelate	MnEDTA	5–12
Manganese oxysulfate		30–50

Manganese is best applied as a foliar spray to correct deficiencies. Soil application is inefficient due to inactivation of applied Mn. Row application of a P fertilizer increases Mn availability and uptake.

Hydroponic Reagent Sources:

Compound	Formula	% Mn
Manganese sulfate	$MnSO_4{\cdot}4H_2O$	24 (14% S)

Concentration in Nutrient Solutions: 0.5 to 2.0 mg Mn per L (ppm).

Symptoms of Deficiency: For dicots, stunted growth with interveinal chlorosis on younger leaves indicates deficiency. Cereals develop gray spots (specks) on lower leaves. Legumes develop necrotic areas on cotyledons (marsh spots).

Symptoms of Excess: Symptoms of Mn excess are brown spots surrounded by chlorotic zones or circles on older leaves. Black specks (measles) on stone fruits, particularly apples, evidence high Mn content in tissues.

Critical Level: 25 mg Mn per kg (ppm) in dry matter.

Reference Plant Content (Markert, 1994): 200 mg Mn per kg (ppm) in dry matter.

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	Mn mg/kg (ppm) in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	25–100
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	50–250
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	40–70
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, prior to flowering)	31–100
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	105
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	50–80
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	40–100
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	30–120
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	25–100
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	50–120
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	25–300
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	20–200
	12 leaves below whorl (prior to tasseling)	20–300
	12 ear leaves (initial silk)	15–300
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	25–350

Plant (Scientific Name)	Plant Part (Time of Sampling)	Mn mg/kg (ppm) in Dry Matter
	25 vegetative stems (full bloom)	30–300
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	25–100
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	60–350
	25 whole tops (early pegging)	100–350
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	200–800
	25 mature leaves from new growth (panicle initiation)	150–800
Rye (*Secale cereale*)	25 whole tops (panicle initiation)	14–45
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 39-day old plants)	40–150
	25 mature leaves from new growth (37–56 days after planting)	60–100
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	10–190
	25 leaves, third leaf below head (grain in dough condition)	8–40
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	20–100
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 after planting)	26–360
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	25–400
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	50–100
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	11–35
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	25–100
Winter wheat	50 leaves, top two leaves (just before heading)	16–200

Toxic Level: >400 mg Mn per kg (ppm) in dry matter.

Agronomic Crops Sensitive to Deficiency: Alfalfa, oats, small grains, sorghum, soybeans, sudangrass, sugar beets, and wheat.

Agronomic Crops Sensitive to Excess: Soybeans.

Major Antagonistic Elements: Ca, Mg, P, and K.

Major Synergistic Elements in Plants: Ca and P.

Soil Conditions for Deficiency: Leached acid soils, neutral to alkaline soils high in organic matter.

Typical Concentration in Foliage of Normal Crops: 25 to 250 mg Mn per kg dry matter, 0.06 to 0.6 mM cell sap content.

Concentration in Environment: 0.001 mol Mn per m^3.

Most Important Sources: Manganite, pyrolusite; accessory in silicates.

Usual Soil Content: 200 to 400 mg Mn per kg (extreme values: 12 to 10,000 mg Mn per kg).

MOLYBDENUM (Mo)

Functions in Plants: Molybdenum is a micronutrient and a component of two major enzyme systems, nitrogenase and nitrate reductase. Nitrogenase is involved in converting nitrate (NO_3) to ammonium (NH_4). The Mo requirement is reduced greatly if the primary form of N available to the plant is NH_4.

Content and Distribution: Leaf content is usually below 1 ppm in dry matter, due in part to low levels of molybdate (MnO_4^{2-}) anion in soil solution. Molybdenum can be taken up in higher amounts without producing toxic effects. However, high content (>10 ppm Mo) forage can pose a serious health hazard to cattle, particularly dairy cows that have sensitive Cu-to-Mo balance requirements. Normal plant content ranges from 0.34 to 1.5 ppm.

Available Forms for Plant Root Absorption: The primary soluble soil form is the molybdate (MoO_4^{2-}) anion, whose availability is increased 10-fold for each unit increase in soil pH. In the soil, Mo is strongly absorbed by Fe and Al oxides whose formation is pH dependent.

Movement in Soil and Plant Root Absorption: Mass flow and diffusion equally supply Mo to roots, although mass flow supplies most of it when soil levels are high. If nitrate is the primary N source, Mo uptake is higher than if NH_4 is equal to or greater than NO_3 as the source of N. In general, P and Mg enhance Mo uptake, while sulfate (SO_4) reduces it.

Mobility: Immobile.

Form Utilized by Plants: Molybdate (MoO_4^{2-}) anion.

Fertilizer Sources :

Source	Formula	% Mo
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$	53
Molybdenum dioxide	MoO_2	75
Molybdenum trioxide	MnO_3	66
Sodium molybdate	$Na_2MoO_4{\cdot}H_2O$	39–41

Mo is best supplied by means of seed treatment.

Hydroponic Reagent Sources:

Compound	Formula	% Mo
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$	53 (6.8% N)

Concentration in Nutrient Solutions: 0.05 mg Mo per L (ppm).

Symptoms of Deficiency: Deficiency symptoms frequently resemble N deficiency symptoms. Older and middle leaves become chlorotic first, and in some instances, leaf margins are rolled, and growth and flower formation are restricted. Cruciferae and pulse crops have high Mo requirements. In cauliflower, the middle lamellae of the cell walls are not formed completely when Mo is deficient. Only the leaf ribs are formed, producing a whip-tail appearance in severe cases. Whip-tail is commonly used to describe Mo deficiency.

Symptoms of Excess: High plant levels do not normally affect the plants, but can pose a problem for ruminant animals, particularly dairy cows that consume plants containing 5 ppm or more Mo.

Critical Level in Plants: Probably 0.10 mg Mo per kg (ppm) in dry matter.

Sufficiency Range: 0.2 to 1.0 mg Mo per kg (ppm) in dry matter.

Excess Level in Plants (affecting the plant only): Not known.

Reference Plant Content (Markert, 1994): 0.5 mg Mo per kg (ppm) in dry matter.

Major Antagonistic Elements: P, K, and S.

Major Synergistic Elements: N and P.

Typical Concentration in Foliage of Normal Crops: 0.5 to 5 mg Mo per kg dry matter, 0.004 to 0.075 mM cell sap content.

Concentration in Environment: 5×10^{-4} mol Mo per m^3.

Most Important Sources: Accessory in silicates; Fe and Al oxides and hydroxides.

Usual Soil Content: 0.5 to 5 mg Mo per kg (extreme values: 0.1 to 80 mg Mo per kg).

NITROGEN (N)

Function in Plants: Nitrogen is a major element found in inorganic and organic forms in plants. It combines with C, H, O, and sometimes S to form amino acids, amino enzymes, nucleic acids, chlorophyll, alltaloids, and purine bases. Although inorganic N can accumulate in plants, primarily in stems and conductive tissues, in the NO_3 form, organic N predominates as high molecular weight proteins in plants.

Plant Content and Distribution: Nitrogen consists of 1.50 to 6.00% of the dry weights of many crops with sufficiency values from 2.50 to 3.50% in leaf tissue. Lower ranges of 1.80 to 2.20% are found in most fruit crops; higher ranges of 4.80 to 5.50% are found in legumes. Critical values vary considerably, depending on crop species, stage of growth, and plant part. Highest concentrations are found in new leaves, with the total plant N content normally decreasing with the age of a plant or any one of its parts.

Ammonium (NH_4^+) fertilized plants are usually higher in Kjeldahl N than those that have mostly nitrate-nitrogen (NO_3^-N) available for adsorption. High-yielding crops will contain 50 to 500 lb N per acre (56 to 560 kg N per ha) with the extent of removal dependent on the disposition of the crop.

The relationships between N and P and N and K are well known. The ratios of N and P and N and K are treated as DRIS norms for interpreting plant analysis results.

The uptake of NO_3 stimulates the uptake of cations; Cl^- and OH^- anions restrict NO_3^- anion uptake. High carbohydrate status enhances the uptake of NH_4), and the uptake of NH_4^+ restricts cations that can lead to Ca deficiency and to reduced K levels.

Nitrogen exists as the NO_3^- anion in main stems and leaf petioles, ranging in concentration from 8,000 to 12,000 ppm during early growth. It declines to a range of 3,000 to 8,000 ppm in mid-season. It is most concentrated at the bases of main stems and in the petioles of recently fully matured leaves. The determination of NO_3 in either stem or petiole tissue is used to analyze N status of plants or to regulate N supplement fertilizer applications. Soluble amino acids are also found in plants.

Available Forms for Root Absorption: Nitrogen exists in the soil as either the NO_3^- anion or the NH_4^+ cation. The uptake of either form is influenced by soil pH, temperature, and other ions in the soil solution. The NH_4^+ cation participates in cation exchange in the soil. Nitrite (NO_2) may be present in the soil solution under anaerobic conditions and is toxic to plants at levels below 5 ppm.

Movement in Soil and Plant Root Absorption: Nitrogen as the nitrate (NO_3^-) anion moves in the soil primarily by mass flow with most of the NO_3 absorbed when it reaches the root surface. Nitrate ions can be readily leached from rooting zones by irrigation water and/or rainfall, or lifted into the rooting zone by upward movement driven by water loss as a result of evaporation at the soil surface and/or evapotranspiration. The other N form, the ammonium (NH_4^+) cation, acts much like the K^+ cation in the soil and its movement in the soil solution is primarily by diffusion.

Ammonium Toxicity: When ammonium (NH_4) is the major source of N, toxicity can occur as seeb often by the cupping of plant leaves, breakdown of vascular tissue at the base of the stem, lesions on stems and leaves, and increased blossom-end rot on fruit.

Mobility in Plants: Mobile.

Forms Utilized by Plants: Ammonium (NH_4^+) cation and nitrate (NO_3^-) anion.

Fertilizer Sources:

Name	Formula	Form	% N
	Inorganic		
Ammonium nitrate	NH_4NO_3	Solid	34
Ammonium sulfate	$(NH_4)_2SO_4$	Solid	21
Ammonium thiosulfate	$(NH_4)_2SO_3$	Liquid	12
Anhydrous ammonia	NH_3	Gas	82
Aqua ammonia	NH_4OH	Liquid	2–25
Nitrogen solutions	Variable	Liquid	19–32
Monoammonium phosphate	$NH_4H_2PO_4$	Solid	11
Diammonium phosphate	$(NH_4)_2HPO_4$	Solid	1–18
Calcium cyanamide	$CaCN_2$	Solid	21
Calcium nitrate	$Ca(NO_3)_2$	Solid	16
Sodium nitrate	$NaNO_3$	Solid	16
Potassium nitrate	KNO_3	Solid	13
	Synthetic organic		
Urea	$CO(NH_2)_2$	Solid	45–46
Sulfur-coated urea	$CO(NH_2)_2$-S	Solid	40
Urea-formaldehyde	$CO(NH_2)_2$-CH_2O	Solid	38
	Natural organic		
Cotton seed meal		Solid	12–13
Soybean meal		Solid	7.0
Milorganite		Solid	12
Sewage sludge		Solid	10–20
Chicken litter		Solid	20–40
Dried blood		Solid	13
Bone meal (raw)		Solid	3.5
	Animal manures		
Dairy		Solid	0.7
Goat		Solid	2.8
Hog		Solid	1.0
Horse		Solid	0.7
Rabbit		Solid	2.0
Sheep		Solid	2.0
Steer		Solid	2.0

Crop response to applied mineral N fertilizer would be expected to be similar regardless of N source if applied as directed. However, the efficiency of N utilization will vary with time, method of application, and N form.

Acidifying Effects of Ammonium Fertilizers:

Fertilizer	Amount of CaO Needed to Compensate for Soil Acidification Induced by 2.2 lb (1 kg) Nitrogen[a]
Calcium ammonium nitrate (27% N)	1.32 lb (0.6 kg)
Ammonia, urea, and, ammonium nitrate	2.2 lb (1 kg)
Diammonium phosphate and ammonium nitrate	4.4 lb (2 kg)
Ammonium sulfate	6.6 lb (3 kg)

[a] On the basis of 50% utilization (*IFA World Fertilizer Use Manual*, 1992, International Fertilization Association, Paris. With permission.)

Hydroponic Reagent Sources:

Compound	Formula	% N
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	11 (21% P)
Ammonium hydroxide	NH_4OH	20–25
Ammonium nitrate	NH_4NO_3	32 (16% NH_4 and 16% NO_3)
Ammonium sulfate	$NH_4(SO_4)_2$	21 (24% S)
Diammonium hydrogen phosphate	$(NH_4)_2HPO_4$	18 (21% P)
Calcium nitrate	$Ca(NO_3)_2{\cdot}4H_2O$	15 (19% Ca)
Potassium nitrate	KNO_3	13 (36% K)

Concentration in Nutrient Solutions: 100–200 mg N/L (ppm); 3 to 4 parts nitrate (NO_3) to 2 and 1 part ammonium (NH_4) for best plant growth.

Fixation Rate by Crops: (kg N/ha): alfalfa, 150; sweet clover, 120; red clover, 90; and soybean, 60.

Symptoms of Deficiency: Slow-growing, weak, and stunted plants; older leaves turn light green to yellow; plants mature early; dry weight, yield, and quality are reduced. The initial and more severe symptoms of yellow-leaf deficiency are seen in the older leaves, since N is mobilized in the older tissue for transport to active growing areas.

Symptoms of Excess: Plants turn dark green and have succulent foliage; easily susceptible to environmental stress, disease, and insect invasion; poor fruit yield of low quality.

Critical Plant Levels: 3.00% total N in dry matter (varies with plant type and stage of growth); 1000 mg per kg (ppm) nitrate-nitrogen (NO_3-N) in leaf petioles.

Reference Plant Content (Markert, 1994): 2.50% in dry matter.

Excessive Plant Level: >5.00% total in dry matter (varies with plant type and stage of growth): >12,000 mg nitrate (NO_3-N) per kg (ppm) in leaf petioles.

Sufficiency Range:

Plant (Scientific Name)	Plant Part (Time of Sampling)	N% in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	1.75–3.00
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	5.00–6.00
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	1.80–1.90
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, prior to flowering)	4.50–5.00
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	2.80
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	4.00–4.50
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	no data
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	3.00–4.50
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	4.50–5.00
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	3.00–3.50
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	2.20–4.00
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	2.70–4.00
	12 leaves below whorl (prior to tasseling)	3.50–6.00
	12 ear leaves (initial silk)	3.00–3.50
Cotton (*Gossypium hirsutum*)	25 vegetative stems	
	(first squares to initial bloom)	3.50–4.50
	25 vegetative stems (full bloom)	3.00–4.30
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	2.00–3.00

Plant (Scientific Name)	Plant Part (Time of Sampling)	N% in Dry Matter
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	3.50–4.50
	25 whole tops (early pegging)	3.50–4.50
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	2.80–3.60
	25 mature leaves from new growth (panicle initiation)	2.60–3.20
Rye (*Secale cereale*)	25 whole tops (panicle initiation)	4.00–5.00
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 29-day old plants)	3.50–5.10
	25 mature leaves from new growth (37–56 days after planting)	3.20–4.20
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	3.30–4.00
	25 leaves, third leaf below head (grain in dough condition)	3.00–4.00
Sudan grass (*Sorghum sudanense*)	15 whole tops (4–5 weeks between clippings)	2.00–3.50
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	4.00–5.50
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 days after planting)	4.30–5.00
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	2.00–2.60
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	2.00–5.00
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	0.53–1.68
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	2.00–3.00
Winter wheat	50 leaves, top two leaves (just before heading)	1.75–3.00

Antagonistic Elements: B, Cu, and F.

Synergistic Elements: B, Cu, Fe, and Mo.

Symptoms of Deficiency: Deficient plants grow slowly, are weak and stunted. Typically, the foliage is light green to yellow. The initial and more severe symptoms of yellow-leaf deficiency are seen in the older leaves, since N is mobilized in older tissue for transport to actively growing portions of the plant. N deficient plants mature early; yield and quality are significantly reduced.

Symptoms of Excess: Plants with an excess of N are dark green and have succulent foliage that is easily susceptible to disease and insect invasion. The plants may lodge easily and are susceptible to drought stress. Fruit and seed crops may fail to yield; fruit and grain are of poor quality.

If ammonium (NH_4) is the only or major form available for uptake, a toxicity condition may break down vascular tissue, thus restricting water uptake. Tomatoes, peppers, cucumbers and other fruiting crops may develop blossom-end rot on the fruit or fruit set may be poor. Symptoms of Ca deficiency may occur if NH_4 is the primary N source. Carbohydrate depletion can occur with NH_4 nutrition, which results in growth reduction.

Most Important Sources: Organic matter and N_2 from the atmosphere.

Usual Soil Content: 0.03 to 0.3% N.

Primary Soil Forms: Plant and animal residues and NH_4^+ and NO_3^- ions.

PHOSPHORUS (P)

Function in Plants: Phosphorus is a major element and a component of certain enzymes and proteins, adenosine triphosphate (ATP), RNAs, DNAs, and phytin. ATP is involved in various energy transfer reactions, and RNA and DNA contain genetic information.

Highest P concentration is found in new leaves and petioles. High-yielding crops contain 15 to 75 lb P per acre (17 to 84 kg P per ha). The P when crops are harvested is considerably less for grain crops when only the grain is removed; most P is left behind in the plants.

The relationships of P with N, Cu, Fe, Mn, and Zn are well known. Ratios of 3:1 of N and P and 200:1 of P and Zn are considered critical. The ratio of N:P serves as a DRIS norm for interpreting plant analysis results.

Soluble P (in 2% acetic acid) is present as the orthophosphate (PO_4^{3-}) anion in main stems and leaf petioles of the actively growing portions of the plant. Its concentration ranges from 100 to 5,000 ppm of the dry weight and can be used to evaluate P status. Critical concentration is about 2,500 ppm.

Available Forms for Plant Root Absorption: Phosphorus exists in most soils in about equal amounts of organic and inorganic forms. Dihydrogen phosphate ($H_2PO_4^-$) and monohydrogen phosphate (HPO_4^{2-}) are the two anion forms. Their ratio depends on soil pH. A combination of Al, Fe, and Ca phosphate is the major inorganic source of P; the relative amounts of the forms are also functions of soil pH. Phosphorus is released into the soil solution by decomposition of crop residues and microorganisms, so they are major sources of P for plant utilization.

Movement in Soil and Plant Root Absorption: The phosphate ($H_2PO_4^-$ and HPO_4^{2-}) anions contact root surfaces primarily by diffusion in the soil solution. However, root interception and an abundance of root hairs will significantly increase opportunities for P absorption. Cool soil temperatures and low soil moisture content can reduce P uptake and create a deficiency.

Mobility: Mobile.

Forms Utilized by Plants: Monohydrogen and dihydrogen phosphate (HPO_4^{2-}, $H_2PO_4^-$), and phosphate (PO_4^{3-}) anions, depending on pH.

Fertilizer Sources:

Source	Formula	% Available P_2O_5	
		Citrate-Soluble	Water-Soluble
20% superphosphate (0-20-0)	$Ca(H_2PO_4)_2$	16–22	90
Concentrated superphosphate (0-45-0)	$Ca(H_2PO_4)_2$	44–52	95–98
Monoammonium phosphate	$NH_4H_2PO_4$	48	100
Diammonium phosphate	$(NH_4)_2HPO_4$	46–48	100
Ammonium polyphosphate	$(NH_4)_3HP_2O_7 \cdot H_2O$	34	100
Phosphoric acid	H_3PO_4	55	100
Superphosphoric acid, polyphosphate	$H_3PO_4 + H_4P_2O_7$	76–85	100
Rock phosphate	Fluor- and chloro-apatites, $3Ca_3(PO_4)_2 \cdot CaF_2$	3–26	0
Basic slag	$5CaO \cdot P_2O_5 \cdot SiO_2$	2–16	—
Bone meal		22–28	—

Phosphorus fertilizers vary considerably in water solubility, and this can affect crop response. Method of application (broadcast versus row) also influences availability, as applied P can be readily fixed by the soil into unavailable forms.

Hydroponic Reagent Sources:

Compound	Formula	% P
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	21 (11% N)
Diammonium hydrogen phosphate	$(NH_4)_2HPO_4$	21 (81% N)
Dipotassium hydrogen phosphate	K_2HPO_4	18 (22% K)
Phosphoric acid	H_3PO_4	34
Potassium dihydrogen phosphate	KH_2PO_4	32 (30% K)

Concentration in Nutrient Solutions: 30 to 50 mg P per L (ppm).

Symptoms of Deficiency: Plants grow slowly and are weak and stunted. They may turn dark green. Older leaves may show purple pigmentation. Since P is fairly mobile in plants, deficiency symptoms initially appear in older tissues.

Symptoms of Excess: Phosphorus excess appears mainly as a micronutrient deficiency. Iron and Zn are usually the first elements affected. High P may interfere with normal plant metabolism. Leaf content above 1% is considered excessive and possibly toxic.

Reference Plant Content (Markert, 1994): 0.20% in dry matter.

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	P % in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	0.20–0.50
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	0.30–0.50
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	0.13–0.16
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth, prior to flowering)	0.26–0.70
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	0.40
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	0.28–0.36
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	0.25–0.50
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	0.28–0.60
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	0.36–0.45
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	0.25–0.30
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	0.25–0.60
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	0.25–0.50
	12 leaves below the whorl (prior to tasseling)	0.30–0.50
	12 ear leaves (initial silk)	0.25–0.45
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	0.30–0.50
	25 vegetative stems (full bloom)	0.25–0.45
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	0.20–0.50
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	0.25–0.50
	25 whole tops (early pegging)	0.20–0.35
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	0.10–0.18
	25 mature leaves from new growth (panicle initiation)	0.09–0.18
Rye (*Secale cereale*)	25 whole tops (panicle initiation)	0.52–0.65
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 39-day old plants)	0.30–0.60
	25 mature leaves from new growth (37–56 days after planting)	0.13–0.25
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	0.23–0.35
	25 leaves, third leaf below head (grain in dough condition)	0.15–0.25
Sudan grass (*Sorghum sudanense*)	15 whole tops (4–5 weeks between clippings)	0.20–0.35
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	0.25–0.50
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 days after planting)	0.45–1.10
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	0.18–0.30
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	0.25–0.60
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	0.11–0.18

Plant (Scientific Name)	Plant Part (Time of Sampling)	P % in Dry Matter
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	0.20–0.50
Winter wheat	50 leaves, top two leaves (just before heading)	0.20–0.50

Critical Plant Level: 0.25% total P in dry matter; 500 mg per kg (ppm) extractable P in leaf petioles.

Antagonistic Elements: Al, As, B, Be, Cd, Cr, Cu, F, Fe, Pb, Mn, Hg, Mo, Ni, Rb, Sc, Si, Sr, and Zn.

Synergistic Elements: Al, B, Cu, F, Fe, Mn, and Zn.

Most Important Sources: calcium (Ca), aluminum (Al), and iron (Fe) phosphates.

Usual Soil Content: 0.01–0.1% P.

POTASSIUM (K)

Function in Plants: Potassium is a major element involved in maintaining plant water status, turgor pressure of plant cells, and the opening and closing of stomata. Potassium is required for the accumulation and translocation of newly formed carbohydrates.

Content and Distribution: Potassium consists of 1.00 to 5.00% of dry weight of leaf tissue with sufficiency values from 1.50 to 3.00% in recently mature leaf tissue for many crops. Potassium is considered deficient or in excess when critical values are less than 1.50% or greater than 5.00%, respectively. In excess, K levels may exceed sufficiency level two- to three-fold. Sufficient K can be as high as 6.00 to 8.00% in the stem tissues of some vegetable crops. Highest concentrations are found in new leaves, petioles, and plant stems. K content decreases with age.

High-yielding crops contain 50 to 500 lb K per acre (56 to 560 kg K per ha). Bananas contain 1,500 lb K per acre (1,680 kg K per ha). Most plants absorb more K than they need. This excess is frequently called *luxury consumption*. Harvesting most fruits removes sizable quantities of K from the soil.

The relationships of K and Mg and K and Ca are well known. High K concentrations first lead to Mg deficiency; when K is in greater imbalance, it causes Ca deficiency. The K:Mg and K:Ca ratios are used as DRIS norms for interpreting plant analysis results. Ammonium (NH_4^+) cations can also play a role in the balance of the three cations, K^+, Ca^{2+}, and Mg^{2+}.

Since K does not exist in a combined form in plants, it can be extracted easily from fresh or dried tissue. The extracted concentration is essentially equal to that determined by total analysis. Some vegetable tips are considered deficient when extracted sap from fresh stems and petioles contains less than 2,000 ppm K, and adequate when the K content exceeds 3,000 ppm.

Available Forms for Plant Root Absorption: The potassium (K+) cation.

Potassium exists in the soil:

- As the K^+ cation in the soil solution
- As exchangeable K^+ on soil colloids
- As fixed K in the lattice of 2:1 clays
- As a component in K-bearing minerals

Equilibrium exists among K in the soil solution, exchangeable K, and fixed K. When K fertilizer is applied to the soil, the equilibrium shifts toward exchangeable and fixed K. The shift is reversed as K is removed from the soil solution by root absorption. As the anion concentration increases in the soil solution, the K level also increases. Although the balance of Ca and Mg related to K in

plants is important, K uptake is not significantly affected by soil Ca levels since Ca moves in the soil primarily by mass flow, while K moves by diffusion.

Movement in Soil and Plant Root Absorption: Potassium moves to root-absorbing surfaces by diffusion in soil solution. The rate of diffusion is very temperature dependent. The extent of root contact (root density) with soil exerts significant effect on uptake. Soil O_2 has a greater effect on K uptake than it has on most other ions.

Mobility: Mobile.

Form Utilized by Plants: K^+ cation.

Fertilizer Sources:

Compound	Formula	% K
Potassium chloride (muriate of potash)	KCl	60–63
Potassium sulfate	K_2SO_4	50–52
Potassium magnesium sulfate (SUL-PO-MAG)	$K_2SO_4 \cdot MgSO_4$	22
Potassium nitrate	KNO_3	44
Potassium hydroxide	KOH	83

Hydroponic Reagent Sources:

Compound	Formula	% K
Dipotassium hydrogen phosphate	K_2HPO_4	22 (18% P)
Potassium chloride	KCl	50 (47% Cl)
Potassium dihydrogen phosphate	KH_2PO_4	30 (32% P)
Potassium nitrate	KNO_3	36 (13% N)
Potassium sulfate	K_2SO_4	42 (17% S)

Concentration in Nutrient Solutions: 10 to 200 mg K per L (ppm).

Symptoms of Deficiency: Potassium-deficient plants lodge easily and are sensitive to disease infestation. Fruit yield and quality are reduced. Older leaves will look as if their edges were burned, a symptom known as *scorch*. Since K is mobile in plants, deficiency symptoms first appear in older tissues. K-deficient plants may also become sensitive to NH_4, leading to a possible NH_4 toxicity syndrome.

Symptoms of Excess: Plants with excess K will become deficient in Mg and possibly Ca due to the imbalance. Magnesium deficiency is most likely to occur first.

Critical Level: 2.00% in dry matter.

Reference Plant Content (Markert, 1994): 1.90% in dry matter.

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	K % in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	1.50–3.00
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	1.20–2.00
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	1.70–2.70
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth prior to flowering)	2.00–3.50
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	1.80
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	1.60–2.60
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	1.00–3.00

Plant (Scientific Name)	Plant Part (Time of Sampling)	K % in Dry Matter
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	1.80–3.00
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	2.00–2.50
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	1.00–1.50
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	1.80–3.00
Corn (*Zea mays*)	15 whole tops (plants <12" tall)	1.70–3.00
	12 leaves below the whorl (prior to tasseling)	2.50–4.00
	12 ear leaves (initial silk)	2.00–2.50
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to intial bloom)	1.50–3.00
	25 vegetative stems (full bloom)	1.50–2.00
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	1.50–3.00
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	1.70–3.00
	25 whole tops (early pegging)	1.70–3.00
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	1.20–2.40
	25 mature leaves from new growth (panicle initiation)	1.00–2.20
Rye (*Secale cereale*)	25 whole tops (panicle initiation)	1.90–2.30
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 29-day old plants)	3.00–4.50
	25 mature leaves from new growth (37 to 56 days after planting)	2.00–3.00
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	1.40–175
	25 leaves, third leaf below head (grain in dough condition)	1.00–1.50
Sudan grass (*Sorghum sudanense*)	15 whole tops (4–5 weeks between clippings)	1.90–3.50
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	1.70–2.50
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 days after planting)	2.00–6.00
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	1.10–1.80
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	2.00–5.00
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	1.14–1.70
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	1.50–3.00
Winter wheat	50 leaves, top two leaves (just before heading)	1.50–3.00

Antagonistic Elements: Al, B, Cd, Cr, F, Mn, Hg, Mo, and Rb.
Most Important Sources: Micas, illite, and potassium feldspar.
Usual Soil Content: 0.2 to 3.0% K.

SULFUR (S)

Functions in Plants: Sulfur is a major element involved in protein synthesis and is a component of amino acids, cystine and thiamine. Sulfur is present in peptide glutathione, coenzyme A, vitamin B_1, and in glucosides such as mustard oil and thiols that contribute characteristic odors and tastes to plants in the Cruciferae and Liliaceae families. Sulfur also reduces the incidence of disease in many plants.

Content and Distribution: Content in leaf tissue ranges from 0.15 to 0.50% of dry weight. Total content varies with species and stage of growth. The N:S ratio may be as important as total S alone or the sulfate and sulfur:total S ratio as indicators of sufficiency.

Cruciferae accumulate three times as much S as P. *Leguminosae* accumulate equal amounts of S and P, and cereals accumulate one third less S than P. Plants may contain 10 to 80 lbs S per acre (11 to 90 kg S per ha). Cereals, grasses, and potatoes remove about 10 lb S per acre. Sugar beets, cabbage, alfalfa, and cotton will remove 15 to 40 lb S per acre (17 to 45 kg S per ha). Sulfur is synergistic with N and P.

Available Forms for Plant Root Absorption: Over 90% of available S exists in the soil organic matter, which has an approximate 10:1 N:S ratio. The sulfate anion is the primary available form found in the soil solution. Most available sulfate is found in the subsoil as the anion can be easily leached from the surface horizon. In addition, availability frequently depends on amounts deposited in rainfall (acid rain) and/or released from organic matter decomposition. At high soil pH (>7.0), S may be precipitated as $CaSO_4$. At lower pH levels (<4.0), the SO_4^{2-} anion may be adsorbed by Al and Fe oxides.

Movement in Soil and Plant Root Absorption: Sulfur moves in the soil as the sulfate (SO_4^{2-}) anion by mass flow and within the soil solution by diffusion. Low soil moisture conditions can inhibit S uptake. Sulfate may precipitate as $CaSO_4$ around the roots if mass flow carries sulfate anions at a rate greater than what can be absorbed.

Mobility: Moderately mobile.

Form Utilized by Plants: Sulfate (SO_4^{2-}) anion.

Fertilizer Sources:

Source	Formula	% S
Sulfur, elemental	S	90–100
Ammonium sulfate	$(NH_4)_2SO_4$	24
Gypsum	$CaSO_4{\cdot}2H_2O$	19
Magnesium sulfate (Epsom salt)	$MgSO_4{\cdot}7H_2O$	13
Potassium sulfate	K_2SO_4	18
Potassium magnesium sulfate (SUL-PO-MAG)	$K_2SO_4 + MgSO_4$	23
Superphosphate (0–20–0)	$CaSO_4$ + calcium phosphate	12
Ammonium thiosulfate	$(NH_4)_2S_2O_3$	26
Sulfur-coated urea	$CO(NH_2)_2$-S	10
Nitrogen-S solution	$CO(NH_2)_2{\cdot}NH_4NO_3{\cdot}(NH_4)_2SO_4$	2–5

Hydroponic Reagent Sources:

Compound	Formula	% S
Ammonium sulfate	$(NH_4)_2SO_4$	24 (21% N)
Calcium sulfate	$CaSO_4{\cdot}2H_2O$	23 (26% Ca)
Magnesium sulfate (Epsom salt)	$MgSO_4{\cdot}7H_2O$	23 (10% Mg)
Potassium sulfate	K_2SO_4	17 (42% K)

Concentration in Nutrient Solutions: 70–150 mg S per L (ppm).

Symptoms of Deficiency: Deficient plants are light yellow-green. Fruits are light green and lack succulence. Roots are longer than normal and stems become woody; root nodulation in legumes is reduced and delayed maturity occurs in grains. Interestingly, S deficiency is desirable in tobacco crops; it produces proper leaf color.

Sulfur deficiency symptoms can be confused with N deficiency symptoms, although S symptoms normally affect whole plants. Nitrogen deficiency symptoms start at older portions of plants. In sandy and/or acid soils, symptoms of S deficiency may occur in newly emerging plants only to disappear as the plant roots enter the subsoil because S as sulfate (SO_4) tends to accumulate in the

subsoil under such soil conditions. Drought conditions may reduce the uptake of S, thereby inducing deficiency.

Symptoms of Excess: Poorly defined.

Critical Level in Plants: 0.30% in dry matter.

Reference Plant Content (Markert, 1994): 0.30% in dry matter.

Sufficiency Ranges:

Plant (Scientific Name)	Plant Part (Time of Sampling)	S % in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	0.15–0.40
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	0.30–0.40
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6" new growth prior to flowering)	0.26–0.50
Bahia grass (*Paspalum notatum*)	50 leaf blades (summer)	0.40
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	0.26–0.30
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	0.25–0.50
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	0.20–0.50
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4–5 week old plants)	0.18–0.50
Corn (*Zea mays*)	15 whole tops (plants <12" tall)	0.21–0.50
	12 leaves below whorl (prior to tasseling)	0.15–0.50
	12 ear leaves (initial silk)	0.15–0.50
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	0.25–0.80
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	0.15–0.40
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior to or at bloom stage)	0.20–0.35
	25 whole tops (early pegging)	0.20–0.30
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	0.20–0.40
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	0.14–0.20
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	0.30–0.55
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	0.15–0.40

Excess (Toxicity) Symptoms: Premature senescence of leaves may occur.

Antagonistic Elements: As, Ba, Fe, Pb, Mo, and Se.

Synergistic Elements: F and Fe.

Most Important Sources: Iron sulfide and sulfate.

Usual Soil Content: 0.01 to 0.1% S.

ZINC (Zn)

Functions in Plants: Zinc is a micronutrient involved in the same enzymatic functions as Mn and Mg; it is specific to the carbonic anhydrase enzyme.

Content and Distribution: Leaf sufficiency range for Zn is 15 to 50 ppm in the dry matter in mature leaves. In some species, visual deficiency symptoms do not appear until the Zn content is as low as 12 ppm. For most crops, 15 ppm Zn in the leaves is considered the critical value. However, a small variation in Zn content, as little as 1 to 2 ppm at the critical level, may be sufficient to establish deficiency or efficiency. Some plants can accumulate Zn concentrations of several hundred ppm without harm. The relation of P and Zn has been intensively studied. Research suggests that high P can interfere with Zn metabolism and affect the uptake of Zn through the roots. High Zn can induce Fe deficiency, particularly in plants sensitive to Fe.

Available Forms for Plant Root Absorption: Zinc exists in the soil solution as the Zn^{2+} cation, as exchangeable Zn, and as organically complexed Zn. Availability is affected by soil pH. It decreases with increasing pH. Availability can also be reduced when available soil P level is very high.

Movement in Soil and Plant Root Absorption: Zinc is brought into contact with plant roots by mass flow and diffusion; diffusion is the primary delivery mechanism. Copper (Cu^{2+}) and other cations, such as ammonium (NH_4^+), will inhibit root Zn uptake. Phosphorus appears to inhibit translocation rather than directly inhibiting uptake. The efficiency of Zn uptake seems to be enhanced by a reduction in pH of the rhizosphere. Plant species that can readily reduce the pH are less affected by low soil Zn than those that cannot.

Mobility: Immobile.

Form Utilized by Plants: Zinc (Zn^{2+}) cation.

Soil–Plant Transfer Coefficient: 1 to 10.

Fertilizer Sources:

Compound	Formula	% Zn
Zinc sulfate	$ZnSO_4{\cdot}7H_2O$	35
Zinc oxide	ZnO	78–80
Zinc chelates	$Na_2ZnEDTA$	14
	NaZnTA	13
	NaZnHEDTA	9
Zinc polyflavonoids	Organically bound Zn	10

Zinc can be applied to plants by soil and foliar applications.

Hydroponic Reagent Sources:

Compound	Formula	% Zn
Zinc sulfate	$ZnSO_4{\cdot}7H_2O$	22 (11% S)

Concentration in Nutrient Solutions: 0.05 mg Zn per L (ppm); can be highly toxic to roots above 0.5 mg Zn per L (ppm)

Symptoms of Deficiency: Zinc deficiency appears as a chlorosis in the interveinal areas of new leaves. The leaves apprear banded. As severity increases, leaf and plant growth are stunted (rosette appearance). Leaves die and fall. At branch terminals of fruit and nut trees, rosetting occurs with considerable dieback of branches.

Symptoms of Excess: Plants particularly sensitive to Fe will become chlorotic when Zn levels are abnormally high (>100 ppm). However, some species can tolerate relatively high Zn (100 to 250 ppm) without significant effects on growth and yield.

Critical Level: 15 mg Zn per kg (ppm) in dry matter.

Reference Plant Content (Markert, 1994): 50 mg Zn per kg (ppm) in dry matter.

Sufficiency Ranges in Plants:

Plant (Scientific Name)	Plant Part (Time of Sampling)	Zn ppm in Dry Matter
Barley (*Hordeum vulgare*)	25 whole tops (emergence of head from boot)	15–70
Cassava (*Manihot esculenta*)	25 mature leaves from new growth (vegetative stage)	40–100
	10- to 30-cm bark sections from main stem just above soil (14-month old plants)	33–43
Alfalfa/Lucerne (*Medicago sativa*)	12 tops (6” new growth prior to flowering)	21–70
	Bahia grass (*Paspalum notatum*) 50 leaf blades (summer)	31
Bird’s-foot trefoil (*Lotus corniculatus*)	50 mature leaves (first flower)	30–50
Alsike (*Trifolium hybridum*)	20 whole tops (first flower)	15–80
Red (*Trifolium pratense*)	15 whole tops (prior to flowering)	18–50
Ladino/White (*Trifolium repens f. lodigense*)	50 mature leaves (prior to flowering)	15–25
Subterranean (*Trifolium subterraneum*)	75 mature leaves from new growth (prior to flowering)	25–50
Coastal bermudagrass (*Cynodon dactylon*)	40 whole plants (4- to 5-week old plants)	20–50
Corn (*Zea mays*)	15 whole tops (plants <12” tall)	25–100
	12 leaves below whorl (prior to tasseling)	20–50
	12 ear leaves (initial silk)	15–60
Cotton (*Gossypium hirsutum*)	25 vegetative stems (first squares to initial bloom)	20–200
	25 vegetative stems (full bloom)	20–200
Oat (*Avena sativa*)	25 whole tops (head emergence from boot)	15–70
Peanut/Ground nut (*Archis hypogaea*)	50 whole plants (prior or at boot stage)	25–60
	25 whole tops (early pegging)	20–50
Rice (*Oryza sativa*)	25 mature leaves from new growth (maximum tillering)	25–50
	25 mature leaves from new growth (panicle initiation)	18–50
Sorghum (*Sorghum bicolor*)	25 whole tops (seedlings <30 cm tall, 23- to 39-day old plants)	30–60
	25 mature leaves from new growth (37–56 days after planting)	20–40
	25 leaves, third leaf below head (plants at bloom stage, heads visible)	15–30
	25 leaves, third leaf below head (grain in dough condition)	7–16
Soybean (*Glycine max*)	25 mature leaves from new growth (prior to pod set)	20–50
Sugar beet (*Beta vulgaris*)	25 leaves (50–80 days after planting)	10–80
Sugarcane (*Saccharium officinanum*)	15 leaves, third leaf from tip (3–5 months after planting)	20–100
Sunflower (*Helianthus annuus*)	25 mature leaves from new growth (summer)	25–100
Timothy (*Phleum pratense*)	25 whole plants (early anthesis)	24–62
Wheat, spring (*Triticum aestivum*)	25 whole tops (as head emerges from boot)	15–70
Winter wheat	50 leaves, top two leaves (just before heading)	20–70

Excess Level in Plants: >300 mg Zn per kg (ppm).

Major Antagonistic Elements: Ca, Mg, and P.

Major Synergistic Elements in Plants: Ca, Mg, and P.

Agronomic Crops Susceptible to Deficiency: Corn, rice, and sorghum.

Soil Conditions for Deficiency: Leached acid sandy soils low in organic matter, neutral to alkaline soils and/or soil high in P.

Typical Concentration in Foliage of Normal Crops: 15 to 75 mg Zn per kg in dry matter, 0.03 to 0.15 mM cell sap content.

High Accumulator Crop: Sugar beet.

Most Important Source: Zinc phosphate, carbonate and hydroxide; accessory in silicates.
Extraneous Sources: Batteries, galvanized metal, brass, rubber products, and fungicides.
Concentration in Environment: 7×10^{-4} Zn per m^3.
Usual Soil Content: 10 to 500 mg Zn per kg (extreme values: 4 to 10,000 mg Zn per kg).

Book List

Each chapter contains a reference list citing publications relevant to that chapter. The publications below are general references and relate to the entire book.

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Agriculture

AGRONOMIC HANDBOOK

Management of Crops, Soils, and Their Fertility

J. Benton Jones, Jr.

Containing essential data and information on the culture of the world's major agronomic grain, oil, fiber, and sugar crops grown on a wide range of soil types, ***Agronomic Handbook: Management of Crops, Soils, and Their Fertility*** serves as a practical reference on the management of crops and soils from planting to harvest.

The handbook provides:

- A list of soil/plant definitions
- Nutrient element requirement levels for the major agronomic crops
- A summary of the characteristics of the major elements and micronutrients in soils and plants
- Diagnostic procedures for assessing the fertility status of soils and the nutrient element status of plants
- Physical and chemical characteristics of inorganic and organic fertilizers
- Global distribution and characteristics of soils
- Production statistics and physical and chemical characteristics of major agronomic crops

Written in the author's trademark, practical style, the handbook describes the genetic history, yield characteristics, cultural requirements, and nutritional requirements of the major agronomic crops; the physical and chemical properties of major soil types; and the composition, formulation, and uses of fertilizers. Crop characteristics are provided including national and international statistics, world production figures, and information on changing crop conditions. With its wide range of fundamental information on crops and soils, the ***Agronomic Handbook*** will be an invaluable reference for anyone engaged in agronomic production, study, and research.

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